9

MICROSYSTEMS RELIABILITY, TEST AND METROLOGY

Chapter Leaders

Frank T. Hartley
Jet Propulsion Laboratory
California Institute of Technology
fhartley@jpl.nasa.gov

Susanne Arney
Lucent Technologies Bell Labs
arney@lucent.com

Fred Sexton
Sandia National Laboratories
sextonfw@sandia.gov

1.0 Introduction....................341
2.0 MEMS Reliability Process....................346
3.0 MEMS Testing....................354
4.0 Predictive Modeling....................368
5.0 Statistical Characterization....................372
6.0 Properties of Manufacturing Materials....375
7.0 Design for Reliability....................380
8.0 MEMS and Metrology....................384
9.0 Challenges in Packaging Reliability........386
10.0 Conclusions....................390
11.0 References....................391

Executive Summary

The international roadmap committee singled out reliability, test and metrology as a key component in the commercial advancement of microsystems. Indeed, reliability and the effective measurement of functionality grounded on metrology is one of the cornerstones to commercial viability of any emerging technology. Yet the man-years of effort required to obtain a robust knowledge of microsystems reliability is very lengthy due to its many faceted domains. This task is a daunting one for the industry and we provide key findings here.

Microsystems' testing has many venues. These include material testing, mechanical testing, imaging, diverse energy domain testing, functional testing, self-testing, and many others. These can be classified as either destructive testing versus non-destructive or semiconductor-like testing versus MEMS-specific. Many testing regimens of microsystems initiate destructive MEMS testing in specific functional domains. However, microsystems are moving toward

semiconductor-like testing, and MEMS-specific testing procedures, which is non-destructive in nature. Many have migrated to self-test for functionality in the final packaged product with in-situ calibration. Further, more and more MEMS-specific test equipment is being developed for this emergent industry.

The pathway for progression to a robust metrology for microsystems is greatly complicated by the lack of a basic understanding of the manner in which materials behave in the micro and nano domains. This leads to a lack of knowledge of basic failure mechanisms. While the pace of increased knowledge in this field is accelerating, we do not expect a full suite of materials knowledge for another ten years. Our contributors have provided taxonomy associated with structural design for reliability that portrays the increasing complexity of mechanisms in terms that directly impact reliability. Class 1 devices are microsystems that have no moving parts and include devices such as ink-jet printheads. These are highly reliable devices easily measured for the most part in today's technology. Class II devices have moving parts but no rubbing or contacting surfaces and include devices like comb drives. Again, today's technology for the most part can test these devices. Class III devices have moving and impacting surface devices such as the Texas Instruments' DMDTM device and special testing procedures are required. Class IV devices have moving parts, and impacting and rubbing surfaces and are typified by some classes of optical switching devices and have testing issues that are considered by the firms solving them as part of their IP portfolio.

A MEMS/MST product is uniquely characterized by its ability to sense, "Think" (i.e. process input signals), act in one or more physical and/or energy domains, and communicate via electrical or RF signals. The product's ability to continue functioning in its designed manner for a given period of time, when subjected to varying degrees of mechanical, thermal, chemical, electromagnetic, frictional, tribological, or other stresses, is a measure of device reliability.

Understanding MEMS/MST reliability and micro-domain failure mechanisms that adversely affect it is a new and relatively unexplored area in the broader fields of reliability and failure analysis. The small dimensionality and the multiple physical and energy domains of MEMS/MST operation, when combined factorially with a vast number of possible MEMS/MST products and applications, make MEMS/MST reliability issues potentially far more complex than for products like ICs that operate primarily in a single (electrical) domain. Moreover, the

complexity of reliability issues may be further compounded because, at this level of dimensionality, manufacturing processes are suspected of having a significantly greater influence on reliability than at more familiar meso or macroscopic dimensions.

This chapter will address MEMS/MST reliability issues, and in particular, reliability issues relating to products "In Use," and issues relating to the manufacturing processes (i.e., "In-process" reliability) for those products. Both directions of study are relevant to understanding the future potential and course of reliability-related research and to delineating MEMS/MST product reliability learning curves. Both are intertwined with the properties of materials and interfaces at micro dimensions. A simple taxonomy of devices will establish categories for reliability studies. A second categorization will be applied to processing technology to assist in identifying promising directions for reliability research. The state of the art in MEMS/MST reliability will be described. Known or suspected reliability bottleneck areas will be identified and suggested directions for reliability research will be enumerated. Finally, although far less is known about MEMS/MST reliability than MEMS/MST manufacturing methods, a consensus timeline for understanding and overcoming MEMS/MST reliability issues will be presented along with a reliability vision statement. Here, we provide a glimpse of the knowledge diffused by MEMS reliability experts in the last two years in addition to timelines for a variety of MEMS reliability related issues

Some specific highlights from this chapter are:

1) A reliability focused taxonomy for MEMS devices.
2) Failure mechanisms inherent in microsystems are explained in depth in addition to their remedies. Modeling will play an increasing role in understanding failure and functionality of microsystems devices.
3) Specific test equipment for MEMS and differing energy domains within MEMS has only become available in the last few years. Our contributors do not forecast a robust suite of test equipment aimed specifically at microsystems being developed for the next 10 years. The accurate prediction of part reliability based on the application of stress and accelerating factors is an important aspect of any reliability analysis. A prediction model for accelerometers is provided as an example.

4) Currently, we do not have a complete metrology library for microsystems materials, mechanical structures, or energy domains. We present the metrology and calibration issues faced by MEMS devices.
5) Novel materials (including nano materials) and non-IC-compatible materials are extensively utilized in microsystems manufacture but are less understood than micro materials. The effect of these new materials on reliability is studied. Processing techniques that enhance reliability are also explained.
6) The increase in functionality being required of many microsystems leads to a concomitant increase in the complexity of its reliability challenge. A basic working knowledge on how to design MEMS for reliability is provided.
7) Some fields of MEMS application and associated reliability and test issues are more mature than others. Maturity by economic necessity enables commercialization. This has indeed been the case in MEMS as reflected by MEMS commercialization and reliability/test initiatives beginning with pressure sensing and ink-jet nozzles, than accelerometers and displays, and most recent optical devices.

1.0 Introduction

Reliability refers to the ability to sort the good devices from the bad ones, and being able to quantitatively predict failure rates of parts delivered to customers. The advancement of reliability information and commercialization of a MEMS product are synchronous. The commercial use of an emergent technology like microsystems is only made possible by a high degree of faith in the reliability and testing of these products. Microsystems devices that have become commercial successes have a robust reliability process and specific testing equipment. As MEMS device complexity has increased over the past few years, there has been a corresponding surge of interest in reliability improvement. Robust reliability and testing has always preceded commercialization, which can be hastened multifold if MEMS reliability can be improved. The roots of the impediments to commercialization of MEMS devices lie in the development of robust test and reliability issues. Reliability is particularly a challenge for MEMS because:

1) Many MEMS applications are in critical systems where failure is disastrous and the requirements for operation are rigorous. MEMS technology has brought about new failure mechanisms that are poorly understood due to the introduction of new processes, materials, and structural geometries.
2) Product replacement costs have driven the need for better reliability, which leads to design tradeoffs.
3) It is in the detail of applying macroscopic mechanical reliability to a microscopic mechanical system and the interaction between the electrical circuitry and the microscopic mechanical system that provides the challenge to MEMs reliability.

Our contributors viewed a MEMS device group as having a commercially acceptable test and reliability process if all the following existed:

1) Commercially available test equipment.
2) A standardized testing process.
3) In-process test capability.
4) End-product test capability involving at least 1 million devices at a given time.

Table 1. Commercialization Timeline for a Selected Group of MST Devices

Product	Discovery	Product evolution	Commercially acceptable reliability process	Full commercialization
Pressure sensors	1954-1960	1960-1975	1985-1990	1990-present
Accelerometers	1974-1985	1985-1990	1996-1998	1998
Gas sensors	1986-1994	1994-1998	2003-2005	2005
Flow valves	1980-1988	1988-1996	1998-2000	2001
Nozzles	1972-1984	1984-1990	1994-1998	1998
Photonics/displays	1980-1986	1986-1998	2002-2004	2004
Bio/chemical sensors	1980-1994	1994-1999	1999-2004	2004
RF switches	1994-1998	1998-2001	2001-2004	2005
Rate sensors	1982-1990	1990-1996	1998-2002	2002
Chromatography	1975-1980	1980-1985	1998-2000	2001
Micro relays	1977-1982	1993-1998	2001-2006	2006

Our contributors have classified MEMS devices into:

1) MEMS devices that already have robust reliability infrastructures.
2) MEMS devices whose reliability infrastructures will take at least 5 years to mature.
3) MEMS devices that at present lack one or more vital components of the reliability process and are expected to take 5-10 years to achieve reliability robustness.

Devices that were seen as robust in the test and reliability arena included pressure sensors, ink-jet printheads, accelerometers, DMD™ devices, certain bioMEMS applications like pacemakers, pressure sensors etc. (see Table 1). MEMS-based devices that at present have undeveloped and emerging reliability infrastructures include optical switching, many RF MEMS applications and bioMEMS applications like drug-delivery systems, protein chips, etc. Devices that are not reliable systems at present are typified by the use of novel materials (Table 2).

Table 2. Timeline of a Reliability Infrastructure for MEMS Devices

	Currently robust	Robust within the next 5 years	Robust in 5–10 years
Commercially available test equipment	Pressure sensors Ink-jet printheads Accelerometers DMD™ devices Microfluidic chips Optical switches	Micropumps Protein chips Microvalves	Micropumps Electronic noses Microgrippers Microspectrometers

Testing norms	Pressure sensors Ink-jet printheads Accelerometers DMD^{TM} devices Microfluidic chips Optical switches RF MEMS Microreactors Microvalves Electronic noses Micropumps Microgrippers Microspectrometers	Protein chips Ultrasound gas sensors Retinal implants	Micropumps Electronic noses Microgrippers
A reliability history equal to or greater than 1 million devices in use	Pressure sensors Ink-jet printheads Accelerometers DMD^{TM} devices Optical switches RF MEMS Microfluidic chips Microvalves	Protein chips Microreactors	Micropumps Electronic noses Microgrippers Microspectrometers Retinal implants
In-process testing	Pressure sensors Ink-jet printheads Accelerometers DMD^{TM} devices Microfluidic chips Optical switches RF MEMS Microvalves	Micropumps Protein chips Microreactors Electronic noses Microgrippers	Micropumps Retinal implants
Non-destructive test procedures	Pressure sensors Ink-jet printheads Accelerometers DMD^{TM} devices Micro reactors Ultrasound gas sensors Optical switches Electronic noses	Safety and arming MEMS device	Micropumps Protein chips Microgrippers
All the above	Pressure sensors Ink-jet printheads Accelerometers DMD^{TM} devices	RF MEMS	Micropumps

The close-link nature of successful commercialization of an MST product and a robust test and reliability procedure that addresses the complexities of MST reliability are illustrated through the selection of four of the product devices presented in Table 1.

1.1. Pressure Sensors

Strain-gauge technology that was the center point of pressure sensors was developed in the 1930's. MST-based strain-gauge technology emerged in the 1950's first as "Silicon Whiskers." In the late 1950's, these gave way to etched silicon substrates in glass solutions. Silicon was the perfect material for strain-gauge applications since strain had differential measurements along different planes in the silicon. Silicon pressure-sensor technology was pushed in the 1950's by the aerospace industry and the U.S. National Institute of Health's need for medical-pressure sensors. Since pressure-sensing MEMS devices were a substitute for other strain-gauge technologies, MEMS test equipment suppliers could move toward testing procedures in silicon relatively quickly. The MEMS-based pressure sensor duplicated the function of the non-MST device exactly, thus evolving functional testing was easy. Pressure sensors thus became the first commercial success of microsystems and the first MST device with a robust set of testing equipment and reliability processes.

1.2. Accelerometers

Accelerometers have been a solution that lent itself to MEMS-based testing technologies. Here, sacrificial surface microsystems technologies, which lend themselves to on-board testing, greatly accelerated the path to commercialization, as did passive-restraint regulation of automobiles that required mandatory use of safety seatbelts or airbags. Vast improvements in functional testing and in-process testing accelerated its commercial acceptance. Today, failure rates of accelerometers are in the single-digit ppm range.

1.3. Optical Switches

Optical switches have presented testing problems never before seen in other MEMS devices. They actuate in mechanical and optical domains and require complex positioning and optical testing procedures. An all-optical switch did not exist and, therefore, Telcordia testing procedures had to be established and met.

Most optical switches initially were Class IV devices with impacting and rubbing surfaces (see our taxonomy). Through the judicious use of design for reliability principles, almost all current designs have eliminated these sources of failure and have now switched positions in the taxonomy graph to Class II devices (Figure 1). However, accelerating failure mechanisms and optical properties have made this a formidable challenge to the MEMS reliability world. Many

micro-optoelectromechanical systems (MOEMS) firms are starting to solve this problem and only recently have MOEMS test companies developed a robust test equipment suite of tools for optical MEMS.

BioMEMS devices are relatively new to the test world. MEMS devices here are rarely new end products but are core products. The full commercialization of the numerous bioMEMS products will take some time since they are fresh out of the R&D phase. The silicon micropump used for drug delivery, for example, has high requirements of accuracy and reliability. Debiotech has managed to reduce chip size 3 times over in 2 years while not compromising its reliability.

Obstacles for commercializing MEMS will dwindle, by building a science-based understanding of MEMS reliability. The elements required to better understand reliability with their current status are:

1) *A primary materials-science understanding of MEMS materials, interfaces, and coatings*. There has been considerable progress to study the properties of materials with reference to MEMS. These include use of self-assembled monolayer (SAM) coatings to eliminate adhesion-release problems, multilayer polysilicon that has negligible residual stress, lead zirconate titanate (PZT) that can couple electrical and mechanical energies, and shaped-memory alloys like TiNi that offer relatively long actuation distances.
2) Tools and techniques to measure physical properties and functionality of MEMS.

These have not developed to such an extent and would achieve stability in the next 5 years. Many new tools for MOEMS, pressure sensors and accelerometers have recently entered the market. Diagnostic tools for bioMEMS devices are also needed.

3) *An understanding of the physics of failure in MEMS devices*. Tools used to study failure mechanisms of IC chips and MEMS are common. New techniques like TIVA (Thermally-Induced Voltage Alteration) have brought a better understanding of MEMS failure mechanisms.
4) *Predictive aging models for MEMS devices.* Both companies and research labs have characterized a predictive reliability model for wear in MEMS. A truly predictable model has to be mathematically sound, scale to large problem sizes, and reliably model physical behavior across a broad range of scales.

Predictive-aging model techniques were recently developed for optical switches, pressure sensors, accelerometers and drug-delivery micropumps. Knowledge of failure mechanisms, use conditions, design requirements and accelerating factors enable a part-reliability model.

Depending on design, different physical effects as described below will dominate microsystem reliability qualification in the future. For example, in many Microsystems (e.g., piezo and diaphragm based designs) macro forces are sufficient to explain the observed phenomenology. However, in other cases, particularly surface MEMS, microscopic forces such as van der Waal capillary and surface tension, can dominate and must be addressed appropriately.

DARPA, NSF, NASA, Sandia National Laboratories, Jet Propulsion Labs, and industrial efforts such as those at Analog Devices Inc. (ADI), Lucent, Motorola, and TI are leading the effort to increased understanding for pre-competitive knowledge sharing. For example, DARPA is currently directing RF MEMS specific reliability efforts.

2.0 MEMS Reliability Process

The three challenges to MEMS reliability testing are considered to be finding the correct failure mechanism, obtaining statistically significant data, and defining a physical model of MEMS reliability. These are considered in the reliability process shown in Figure 1.

The most common and important step in the reliability process is to gain a complete understanding of the failure mechanism process. Research in MEMS failure mechanisms is considered still in its infancy and the views of our contributors are explained in the rest of this section.

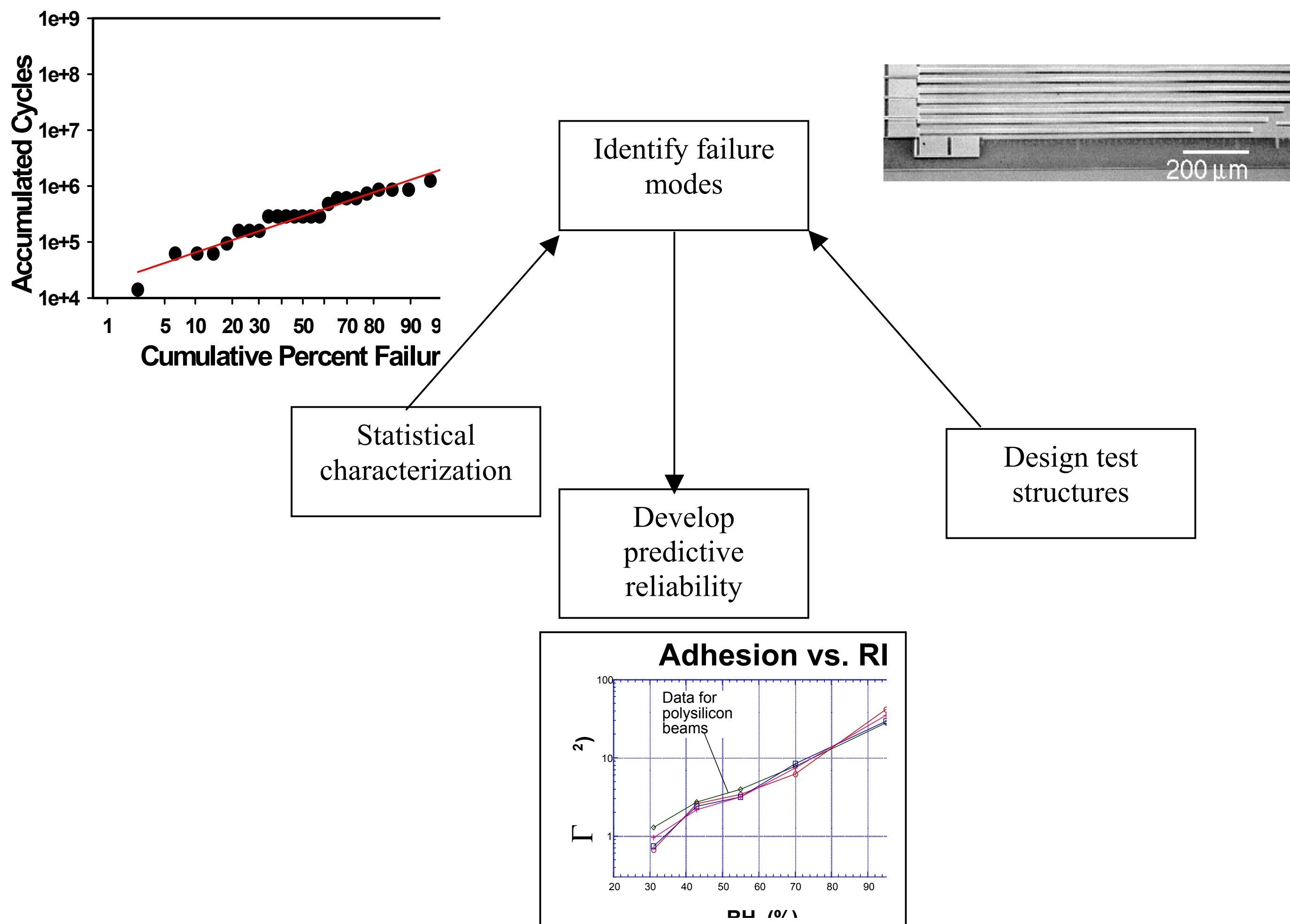

Figure 1. MEMS Reliability Process. Source: Sandia National Laboratories.

2.1. Reliability Taxonomy based on Failure Mechanisms and Modes

In considering "in-use" reliability issues for MEMS/MST products, four classes of devices may be defined for the purpose of allocating reliability risk. These are listed in Figure 2.

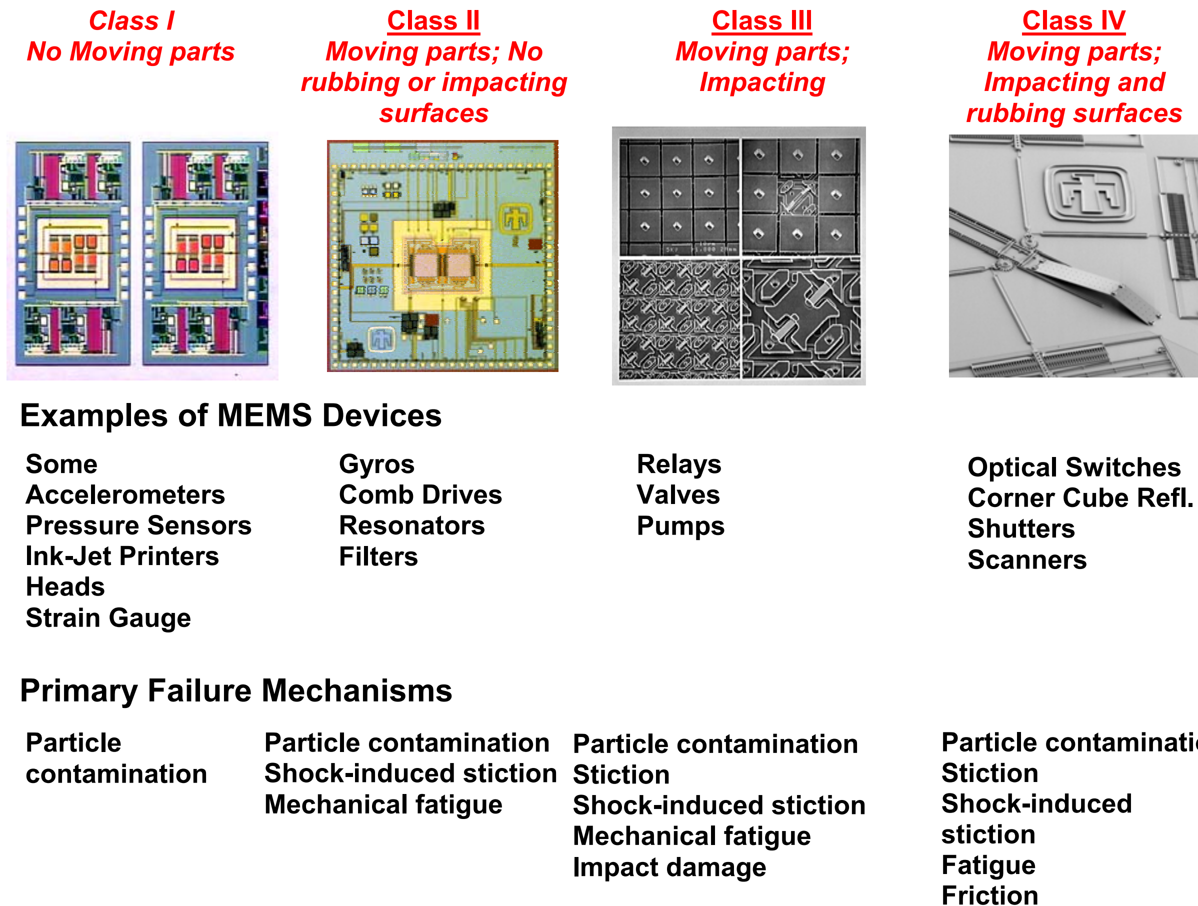

Figure 2. A Taxonomy of Devices for Assessing "In-use" MEMS/MST Reliability Issues According to Failure Mechanisms. Source: Sandia National Laboratories.

With respect to IC-like processing, MEMS/MST technologies leverage the existing base of IC manufacturing know-how. However, MEMS/MST products are used in multiple physical or energy domains (e.g., chemical, magnetic, fluid processing, etc.) and the resultant functional, test, and reliability requirements for MST are fundamentally different from those for IC applications. Therefore, processes are adapted (e.g., a stress-free silicon-nitride coating), new processes are invented (e.g. an anisotropic KOH etch or a new deposition process), new materials are used (e.g. a wear-resistant coating), and new processes combined with new materials are invented (e.g. innovative microstructuring for metal or plastic devices). Here too, a

categorization can be provided for process improvement (Table 4). The state of the art can be documented using the taxonomies of Tables 3 and 4.

Table 3. Product/Reliability Issue Matrix

Product	Class	Operating Reliability Issues										Non-operating Reliability Issues										
		Mechanical Wear	Fracture	Fatigue	Optical Degradation (Use)	Charging	Shock	Vibration	Dielectric Breakdown	Change in Friction		Radiation	Thermal Degradation	Thermal Cycling	Humidity	Shock	Vibration	Stress-corrosion cracking	Creep	Environmental Degradation	Optical Degradation	Stiction
DNA Sequencers	I																			x		
Microfluidics (electrostatic)	I								x											x		
Nozzles	I																			x		
Chemical Sensor	I											x								x		
Accelerometer	I or II	x	x	x		x	m	m		x		x			x	x	x		x			x
Pressure Sensor	II		x	x			x	x					x	x					x	x		
Gyro	II					x	x	x				x			x	x	x					
Microfluidic Pumps (Flex)	II		x	x			x	x								x	x	x	x	x		x
Waveguide Switch	II		x	x			x	x							x	x	x	x	x	x		x
Thermal Actuator	III	x					x	x					x	x		x	x					x
Valves	III	x	x	x			x	x					x	x		x	x	x		x		x
Microrelays	III	x	x	x		x	x	x	x	x					x	x	x	x	x			x
Electrostatic Actuator	IV	x	x	x			x	x		x					x	x	x	x	x			x
Optical Shutter	IV	x	x	x			x	x					x	x	x	x	x					x
Mirror Device	IV	x	x	x	x		x	x					x	x	x	x	x				x	
Microfluidic Pumps (Rubbing)	IV	x	x	x			x	x		x						x	x	x		x		x
Geared Devices	IV	x	x	x			x	x		x			x	x	x	x	x	x	x	x		
Microturbine/Fan	IV	x					x	x		x			x	x		x	x	x	x	x		

x = is an issue **m = measured quantity**

Table 4. A Taxonomy of "In-process" Reliability Issues. Source: *Sandia National Laboratories*

Class	Characteristic
I	Incremental improvement of existing process
II	Innovative manufacturing process
III	New materials, existing processes
IV	New materials combined with new processes

With respect to the "In-process" reliability issues, current methodologies such as test-structure use for reliability monitoring will be discussed, and the manufacturing practices of a number of foundries currently manufacturing MEMS/MST products will be assessed from a reliability standpoint. A precedent for doing this was established by the "Best Practices" studies of Hodges et al. (Berkeley).

The “In-use” reliability state-of-the-art demonstrates the clear need for defining standard procedures for the measurement of various parameters such as fracture strength, wear resistance, etc. There are no current standards in this regard, nor is there a consensus on determining which materials parameters are important.

2.2. Proposed Solutions and Suggestions for R&D

One should be able to conclude whether major reliability differences occur when existing processes and materials are used for MEMS/MST fabrication, or when new processes and materials are used. In the latter case, it is suspected that many reliability parameters need to be determined. For evaluating in-process reliability issues, there is a clear need for establishing consensus on measurement procedures on a variety of materials and structural parameters. These and other R&D directions will be discussed in detail.

The cost of MEMS/MST development, and ultimately the reliability of MEMS/MST, is adversely affected by the numerous design iterations required to characterize the physical properties of materials and to “Tune” the physical structure of devices with respect to these properties. The industry needs handbooks on “MEMS/MST Quality and Reliability” and “MEMS/MST Strengths of Materials.”

Testing MEMS/MST devices is a major cost for the industry and testing protocols and techniques are crucial in accelerated life-test validation. The development of new stress-testing procedures and systems is required. Product assurance and failure identification mechanisms of Atomic-Force Microscopy (AFM), micro X-rays, ultrasonic microscopy and Scanning-Electron Microscopy (SEM) are being applied to fracture, wire-bond, structural faults, debris, and delamination analysis for the IC industry. These instruments need also be applied to the analysis of MEMS/MST.

Assurance of MEMS/MST requires thorough process validation, proof of process building and detection by inspection—all procedures requiring stable, mature and large-scale production programs.

2.3. Failure Mechanisms

The significance of understanding failure mechanisms is demonstrated by the path tread by the IC industry. IC-related failure mechanisms like electromigration, time-dependent dielectric

breakdown (TDDB), stress voiding, and hot-carrier damage, were studied in depth which lead to foundry design rules that has mitigated failure rates enormously. The vast insight that the IC industry developed in failure mechanisms has resulted in incredible strides in reliability, notwithstanding the rapid decrease in technology node size. Hence a brief description of the failure mechanisms that affect MEMS devices is given. To design accelerated testing methods, MEMS failure mechanisms have to be understood in depth (Table 5).

Table 5. MEMS Failure Modes

Mechanical	**Optical**	**Electrical**
Friction, wear, stiction, fatigue, work hardening, fracture, thermal-coefficient mismatch, residual stress, compensation, creep, flow, transport	Reflecting surfaces, cavities, oxidation, grain growth	Insulator breakdown, metals, charging, drift, shorts, opens, arcing, electrostatic discharge, ablation
Failure-inducing methodology	**Failure-inducing methodology**	**Failure-inducing methodology**
Shock testers Shaker table Accelerated cycling Accelerated storage	Resonant mode (mechanical over-drive) Thermal excursions Voltage electrical/mechanical over-drive)	Voltage (electrical/mechanical over-drive)

The most dominant MEMS failure mechanisms occur in solder joints and connectors. To gain understanding of a fracture process occurring at the boundary of two dissimilar materials, when the mismatch of elastic modulii is of paramount importance, it is common to subject a specimen to a fracture test and then perform the so-called “Post-mortem” evaluation of the fracture surfaces. Due to unique dimensions and properties of microstructures, and in view of their various adhesion/cohesion and geometrical configurations, it’s appropriate to subject the dynamic member to a fracture test under pre-determined loading and environment conditions. Next, a fractographic examination, involving skillful use of microscopy, should reveal a number of details and patterns, which are a record of the various mechanisms and modes of fracture.

Understanding these intricate details, in turn, should lead to a better design that utilizes a combination of materials and geometries, which offset the influence of the factors that induced the brittle failure. The primary tools for this investigation are the electron and atomic-force microscopes (not excluding some optical magnifying devices) to observe the topographical details on the uncontaminated surface of freshly generated fractures. Available 3D graphics software (similar to routines used in SOAP '98) would be used to process these data to better reveal certain characteristic patterns such as river marks and Riedel lines which are typically associated with rapidly propagating fractures.

Many MANCEF members have expressed interest in exploring micro topographical analysis as an identifier of root-cause-of-failure and as an indicator for failure corrective action and paths to improvement. MANCEF will instigate exploratory investigations on various members' mechanical affect on transducers (i.e. accelerometer and pressure sensors). Pending success, the techniques will be expounded and the program expanded to include more members and more transducers.

Mechanical failure mechanisms due to contacting, sliding, or rubbing MEMS device surfaces, as well as many solutions, have been widely reported. Stiction (static friction, or adhesion) can be designed out both during fabrication and during operation. During wet chemical sacrificial-layer release etches, fabrication techniques including supercritical CO_2 drying (Jafri, 1999), sublimation, and self-assembled "Anti-stiction" monolayer films prevent capillary forces from drawing compliant MEMS structures into contact with one another during the drying step. "In-use" stiction, friction and wear of silicon MEMS surfaces can be further reduced through the use of controlled levels of humidity (Tanner, 1999); gettering (Kullberg, 1999); anti-stiction coatings (Tanner, 1999); and selective tungsten coatings (Mani, 2000). Packaging techniques can further control outgassing and moisture or other contaminant gas ingress and reduce "In-use" stiction. Design techniques to prevent both "Release-etch" and "In-use" stiction include the use of very stiff structures, flexure or bending structures without bearings, and the use of "Dimples" or other surface modifications which reduce the contact area between two MEMS surfaces (Komvopoulos, 1996). Finally, operational choices in conjunction with MEMS actuator and flexure design can reduce or altogether eliminate the possibility of surfaces touching one another due to vibration, shock or electrical overvoltage.

A wealth of prior knowledge from integrated and photonic circuit reliability physics provides a framework for optimizing electrical and optical aspects of MOEMS reliability, which derive from a combination of surface and bulk material effects (Arney, 2001). As with mechanical reliability phenomena, design, materials and fabrication choices all impact the extent of these phenomena. Surface leakage currents, anodic oxidation, charge trapping/generation, shorting, open circuits, or capacitance changes can be controlled through appropriate attention to materials choices and surface science. Elimination of surface roughness or asperities can reduce the probability of electrical field concentration, arcing, and related surface electrical breakdown, and greatly enhance reflectivity in MOEMS devices. Materials and fabrication choices similarly can be optimized to reduce the effects of thermally driven Coefficient of Thermal Expansion (CTE) mismatch, delamination, curvature, deformation, or residual-stress relaxation, optical-wavelength absorption and any associated degradation of reflecting surfaces. While any number of phenomena, as listed in Tables 4 and 5, may impact "Poorly Designed" MOEMS or MEMS device reliability, real-world commercialization of diverse MEMS devices (accelerometers, pressure transducers, ink-jets, projection displays, micromirror-based optical cross-connects or OXCs) provides evidence that the technology is inherently sound when properly executed. Appropriate design, fabrication, packaging, and manufacturing choices, fundamentals-driven reliability, physics, experimental and theoretical protocols, and a design-for-reliability paradigm that concurrently optimizes multiple aspects of MOEMS device development are critical in transforming specific MOEMS research ideas into lightwave-network-element-quality-components.

Failures in bioMEMS are as rampant as those in MEMS /MOEMS. Two approaches can be used to generate DNA chips, the application of DNA oligonucleotides to the chips, or the synthesis of "In Situ" on the chip. The addition of a series of oligonucleotides to the chip can be expensive, since each one must be synthesized separately. However, synthesis on the chip can result in the presence of oligonucleotides that are incomplete, i.e. failure sequences. The presence of failure sequences might interfere with the quality of the assay. This might arise if hybridization occurs between failure and spurious sequences within the sample. If the assay conditions have been set well, hybridization should not take place, as the bond energy should not be sufficient. However, by maximizing the coupling efficiency of the synthesis through advanced technology or improved chemistry, the amount of failure sequences can be kept to a minimum.

3.0 MEMS Testing

Simple methods for testing and characterizing failure modes of MST devices are not common. The consequences of this include the requirement of many costly prototypes for the design engineer and increased fabrication costs since defects can go undetected until late in the fabrication cycle.

The development path of MEMS testing methodologies is similar to that of microelectronic circuits of the past. Failures analyses techniques for inspecting MEMS devices have been borrowed from microelectronics, optical microscopy, scanning-electron microscopy, focused ion beams, and acoustic or infrared microscopy, and are changing.

MEMS manufacturers have battled electrical shorting and until recently had no non-destructive technique in sight. Thermally Induced Voltage Alteration (TIVA), a new failure analysis technique developed by Sandia National Laboratories, has attracted the attention of optical MEMS companies to investigate this failure mechanism (Walraven, 2000). This tool will be increasingly applied in the next 5 years in the MEMS industry.

MEMS are mostly analog devices, and thus MEMS testing is very similar to analog and mixed-signal electronic testing. Embedding MEMS components can have a negative effect on the entire system since reliability models are usually not well known. Parallels between the state of MEMS testing today and microelecronics testing in the last decade are presented in the Table 6.

Table 6. A Comparison between MEMS and IC Systems (Courtois et. al., 2000)

Integrated systems testing	**Digital circuits 1980 - ……**	**Analog and mixed-signal circuits 1990 - ……**	**Microsystems 2000 - ……**
Failure mechanisms, fabrication defects	Latchup, dielectric breakdown, electrical overstress, metal stress voiding and electromigration, hot carrier effects, contaminants		… and in addition, micromachining defects, fatigue, friction...

Fault models	Stuck-at, stuck-on, stuck-open, bridge, …	Parametric and catastrophic faults (electrical shorts and opens)	… and in addition: shorts and opens in thermal, mechanical domains…
Test techniques	Concurrent fault simulation (VHDL, HSPICE) Diagnostic (fault dictionary…) BIST (full/partial scan path, LFSR (Linear Feedback Shift Register) …	Sequential fault simulation (HSPICE, SABER,VHDL-AMS), ATPG (sensitivity …) Diagnostic (e.g. frequency signature) BIST (no general solution)	Modeling of microsystems at circuit-level (HDLs) and transposition of techniques developed for microelectronics, BIST

3.1. Fault Modeling

An in-depth analysis of defects and failure mechanisms leads to the understanding of device failure modes and to robust fault modeling. Deriving satisfactory fault models is associated with the level of description and procedures used for simulation. MEMS/MST design is an intricate process that is not approached in the traditional hierarchical and analytical style of microelectronics. By modeling faults at the circuit level, techniques developed for testing analog microelectronic circuits can be transformed to suit MEMS devices (Mir, 1999).

This is possible for classes of MEMS accurately described by ordinary differential equations, and represented as networks of lumped-parameter elements like capacitances and resistances. These networks must obey basic energy conservation laws (Courtois, 2000), such as the summation of quantities (like voltage, force and heat) around a closed loop must equal zero like Kirchhoff's current and voltage laws. Faults have physical causes called defects that consist of an impurity, such as a dust particle. These defects at the layout level of the chip, are rendered into electrical faults and are translated into logical faults such that they can be tested with logical signals (0s and 1s). This mapping of defects into electrical and thereafter logical faults is called fault modeling. A test generation process is very complex because the number of possible faults can be very large. A good testing generation process should have a test for every conceivable

fault. Thus developing a robust fault model is critical for MEMS testing since the number of possible faults can be large in comparison to ICs.

MEMS devices are easily rendered to Fault Based Testing (FBT) by using an analog Hardware Description Language (HDL^{TM}). Since 80% of the cost of MEMS devices is associated with packaging, FBT is very useful for testing MEMS. It doesn't destroy the package.

3.2. Test Generation

On-chip testing of analog and mixed-signal parts is expected to improve considerably. That will bring MEMS parts into the new generation of highly heterogeneous integrated devices Analog HDLs (A-HDLs) are used to enable efficient integration of design and test for MEMS parts and by using a suitable circuit-level description for fault injection and simulation (Courtois, 2000). A Computer-Aided Test (CAT) suite can be used for injecting faults in HDL design descriptions, performing fault simulation and producing test vectors as shown in Figure 3.

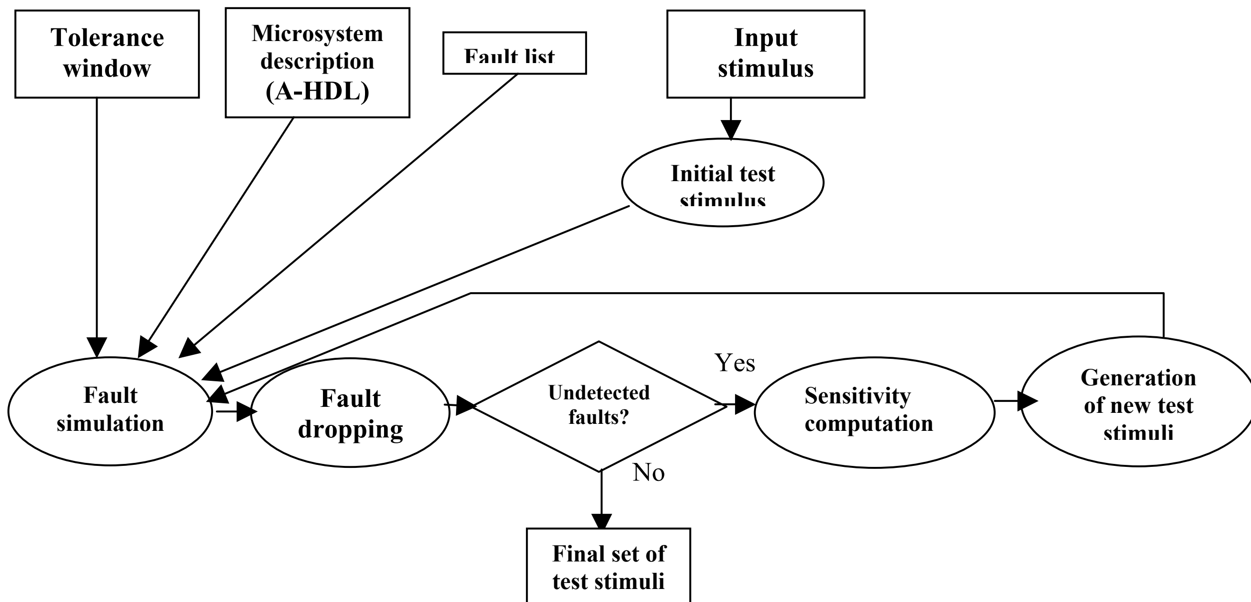

Figure 3. MEMS Test-generation Environment (Lubaszewski, 1998).

The user gives the input stimuli range to the test-generation tool. For the initial test input, the procedure checks by fault simulation which faults in the fault list are detected and by measuring the test parameters. Detected faults are dropped from the fault list. Undetected faults are then checked by two new input stimuli, one higher and another lower than the initial value. The still

undetected faults are partitioned into two new lists, one containing those faults for which the sensitivity of the measuring parameter is higher for higher input stimuli, and another containing those faults for which the sensitivity is higher for lower input stimuli. The procedure is recursively applied to the new lists until all faults are detected (Courtois, 2000).

3.3. Built In Self Test (BIST)

Manufacturing discrepancies such as over-etching and under-etching can be mistaken for stiction and minute particles. The similarities can result in otherwise perfect devices being mistakenly declared defective due to minor manufacturing errors. Built-In Self Test (BIST) can help avoid this by locating the source and nature of a defect accurately.

LogicVision, Inc. introduced the first commercial BIST solution for mixed-signal ICs in 1997. Since these ICs are very similar to MEMS devices, BIST solutions for MEMS will be extensively used in the next 5 years. At present, only a handful of MEMS companies use BIST like EG&G sensors. BIST techniques are gaining popularity among IC chip manufacturers since it enables precision measurements on-chip in a relatively short time. The steady increase in the complex electronic circuitry in MEMS/MST devices and of the mounting gap between internal clock and I/O frequencies will increase the cost and complexity of exterior electronic testing, due to the rise of tester memory requirements and test time. This will drive MEMS/MST technology towards BIST techniques. All high-end MEMS device manufacturers will start to include test logic on their products in the next 3 years.

A major challenge for applying BIST techniques to MEMS is the multi-domain nature of the sensing parts, which requires special test equipment for stimuli generation. Increased levels of integration in MEMS-based devices raise major test concerns, which cannot be solved by implementing conventional techniques. All techniques developed in the past for the self-test of microelectronic parts can be applied in the self-test of MEMS parts. The use of MEMS self-test techniques has already been considered in some of the first successful sensors such as airbag accelerometers (Terry, 1989).

MEMS devices that work in different energy domains need to have non-electrical test stimuli that can be induced on-chip by means of electrical signals. At present, this is the most viable BIST approach for MEMS parts embedded in integrated systems (Charlot, 2001). MEMS devices like sensors are usually located in places often hard to access for regular maintenance.

Adding a self-test function provides an adequate mechanism for improving device reliability and achieving device calibration. The authors expect that almost 90% of all MEMS devices in the next 8 years will have BIST in them. In accelerometers, an electrostatic force is used to displace the suspended mass during self-test. In the case of self-testing pressure sensors, sensing membrane displacement can be achieved by means of thermomechanical actuation of a bimetallic strip.

Most MEMS devices sense physical signals (acceleration, force, pressure, radiation) and convert them into electrical signals processed by the associated electronics. For self-test, these signals must be generated on-chip during a test phase that must be as short as possible using the most standard test equipment that has only electrical inputs and outputs. The goal is thus to find a way to generate on-chip the required physical stimuli under electrical control, avoiding the use of specific signal sources. This reduces the requirements in test equipment during manufacturing test and provides the means for the implementation of a self-test function that can be used for field testing. By replacing the original physical stimuli given to a MEMS device with electrically induced stimuli, it is possible to send electrical test vectors to obtain the more useful electrical characteristics of the MEMS device. Parallel-plate capacitors for capacitive accelerometers, piezoresistive components for accelerometers, pressure sensors and tactile sensors, and thermopiles for infrared sensors can be used to achieve this conversion (Charlot, 2001).

An example of self-test implementation is found in Analog Devices' ADXL series of capacitive accelerometers. It must be noted that for production testing, the manufacturer does not normally use this feature. It is the customer's prerogative to use this feature. The activation of a self-test pin sends a voltage impulse to additional interdigitated fingers of the accelerometer, thus inducing an electrostatic force, which mimics an acceleration force. It has recently been shown that most typical accelerometer defects impact most important device parameters such as natural resonance frequency (Deb, 2000). Since the analysis of the response allows the extraction of functional parameters such as the resonance frequency, it may be possible to exploit the self-test features for production testing.

3.4. Cost of Testing

The cost of MEMS testing has increased due the various energy domains in which MEMS devices operate. Approximately 20-30% of the final cost of a MEMS device is attributed to

testing. A disruptive technology like MEMS can displace existing technology completely only when the cost of testing is reduced substantially and value-added testing techniques are added at the early stages of the market. The material costs of matured MEMS products like pressure sensors and accelerometers have become less significant in comparison to reliability and testing. As novel MEMS devices are manufactured in high volume, the costs of packaging and testing will be a prime consideration.

There are discrete differences in the test requirements for MEMS devices as they evolve through their product development life cycle. In each phase of development, the importance of test and the cost thereof is described below (Klim, 2001).

3.4.1. R&D phase

Tools available at this stage have to help MEMS design engineers completely study the reaction of their devices to a wide variety and range of stimulus and inputs. Test and measurement equipment has to be built in-house. This increases testing time requirements and hence the cost.

Costs incurred at the R&D phase have to be greater than that incurred during the pilot phase, to help in the decision making process at the pilot phase and thus reduce MEMS test costs, and to swiftly enter the production stage. Increased testing at this phase ensures that only the best products will evolve to the pilot phase.

3.4.2. Pilot phase

During this phase, the test system has to have the capacity to execute the types of tests that will eventually be employed during production stage. The functionality and commercial viability of the device after deriving its costs has to be arrived at at this stage. The data is essential to ensure that the product is relevant in the market, and is worthy of continued development. Rigorous package testing, performance testing and reliability testing implemented at this stage are essential to ensure a successful product in the market.

3.4.3. Production phase

The test stratagem here focuses on high-volume production of the device. The test system has to be optimized with regard to throughput without reducing measurement accuracy. Parallel

testing capacity should be achieved at this stage. Costs incurred at this stage are greater than those at the pilot phase but lower than those at the R&D phase (Figure 4).

3.5. Specific Test Equipment for MEMS

Reliability testing or accelerated testing is used to find the failure modes and to find the real limits of the devices by operating the device at extreme conditions. Reliability testing also often entails identifying small changes in device performance that precede catastrophic failure, and hence it requires high precision and accuracy.

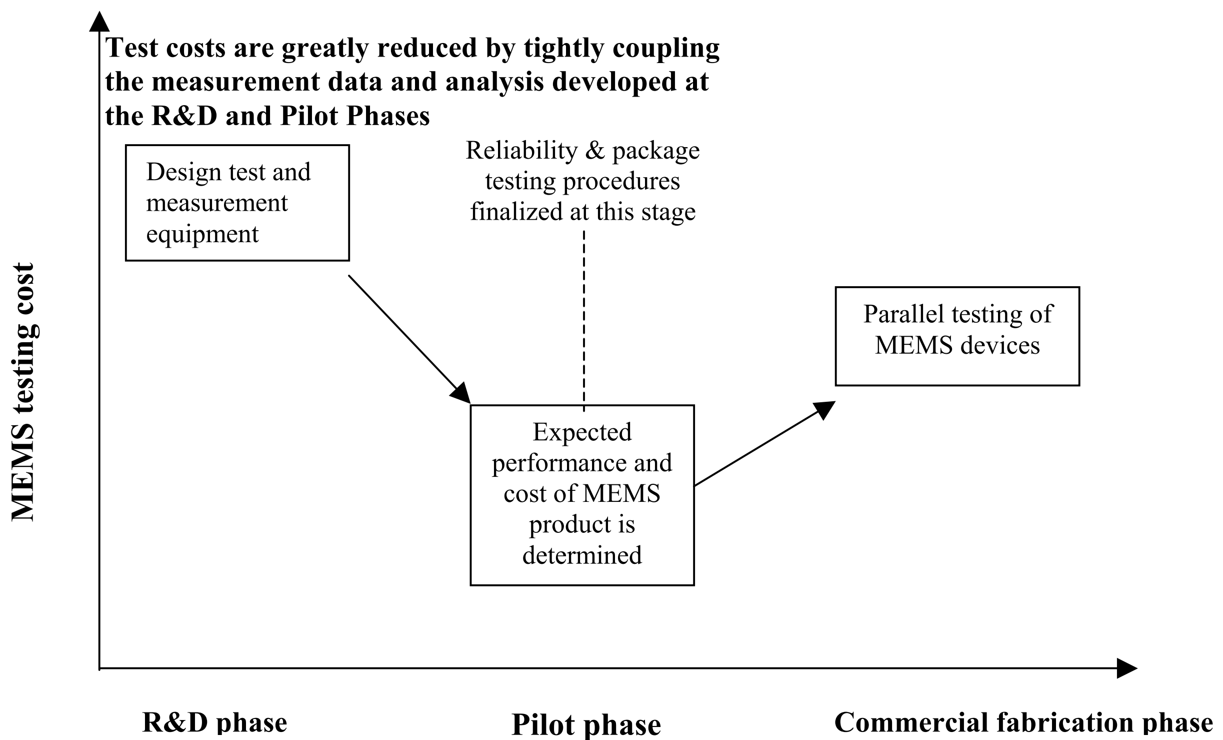

Figure 4. MEMS Product Development Life-cycle and Test Costs.

3.5.1. Generic tester

For all semiconductor testing, electrical stimuli are mature and temperature-testing stimuli are also well understood. In the case of MEMS/MST, in addition to the electrical and generally the temperature stimuli, there is an additional physical stimulus and the need for the transduction of this measured through the transducer housing. The pertinent measured parameters are offset, sensitivity, linearity error and hysteresis as well as consideration of the dependent variables (i.e.,

temperature, magnetic field etc.) and coefficients of offset, sensitivity and hysteresis. The combinatorial testing load for the MEMS/MST transducer increases factorially, over that of temperature and voltage characterization for semiconductors, for each additional physical variable. Furthermore, the contemporary trend of hybridizing MEMS/MST transducers with CMOS analog and/or digital logic to create smart sensors results in both transducer and sensor output domains that need to be separately measured and correlated. This is equivalent to an additional variable. Clearly, the testing of MEMS/MST is challenging even for single devices but the tasks escalates dramatically in complexity and cost for the "Ganged," simultaneous testing of multiple devices.

High-volume production testing stations can cost millions of dollars and testing costs for a transducer can be as high as a third of its selling price. The major components of these test stations are common, with physical stimulus and module fixtures changing for different measurements (pressure, acceleration etc.). Such modular testing platforms are a common requirement for the industry. MANCEF, with SEMI support, is considered an appropriate forum to refine and consolidate a specification for this equipment. Figure 5 shows how a generic MEMS tester should operate.

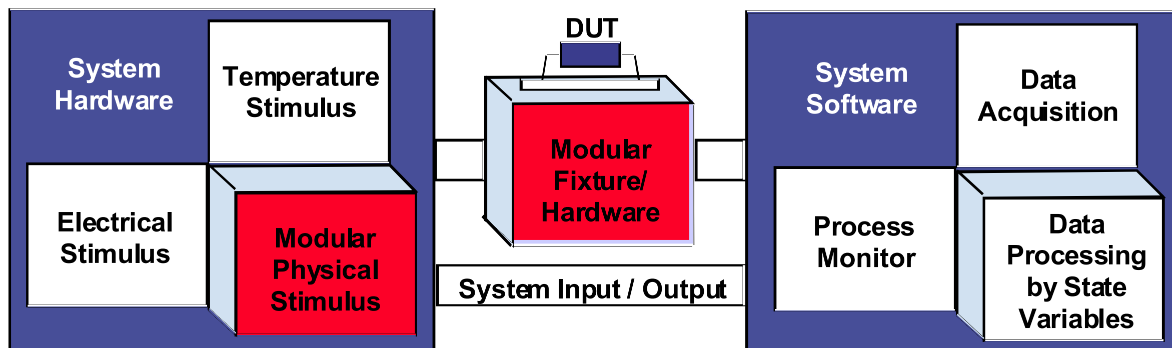

Figure 5. A Generic MEMS Tester.

3.5.2. Mechanical shock

Dynamic mechanical stress testing involves dropping packaged parts from various heights, different orientations, and for different numbers of cycles. Statistical failure analysis is then applied to the failed populations to identify failure modes from shock energy and number of stress cycles. No one in the industry is happy with this drop test and would much prefer a

controlled dynamic stress (shock) test methodology that was measurable, repeatable and a more direct precursor of failure modes.

Caltech's Jet Propulsion Laboratory (JPL) has extensive experience in mechanical stress-testing methods that extend from shaker synthesis to resonant-plate and pyro-shock techniques. The resonant-plate method has the advantage of a stiff, free-free, metal plate that can exhibit very high frequency resonances. The article to be tested is mounted to a steel plate that is suspended in mid-air. A metal pendulum is then swung into contact with the plate, inducing transient vibration. JPL has created a hybrid resonant plate-pyrotechnic simulator. This Mechanical Impulse Pyro Shock (MIPS) tester encapsulates the basic resonant-plate shock-test parameters in a single, relatively compact machine where the plate is excited into resonance by the impact of a pneumatic actuator on a moveable bridge, instead of by a pendulum. The MIPS shock pulse is tailored, by adjusting the dimensions of the resonant plate, the strike location of the hammer, the hammer material, the size of the hammerhead, and the duration of applied pulse. MIPS, tailored to the shock energies and spectrums required of different transducers, has vastly superior dynamic stress characteristics than the drop test. Further, the shock spectrum can be measured, transducer data can be measured during testing, and multiple transducers can be tested simultaneously.

Under MANCEF, JPL will demonstrate the superiority of this mechanical shock test. For those members who want to begin such testing, JPL will help design specific MIPS and resolve how best to correlate its failure assurance with that of conventional drop tests.

3.5.3. Degradation

Absolute pressure

The long-term stability of absolute-pressure transducers is, in large part, determined by the stability of their internal vacuum. As the period of performance increases (already ten years for the automotive industry and longer for space applications), the measurements of leak-rate and hysteresis become increasingly difficult. Sensor material outgassing, "Getter" material's characteristics, hermetic-seal integrity and the porosity of sensor materials are all stability determining parameters.

Absolute-pressure measurement is dependent on so many variables (which are themselves functions of other parameters such as temperature and thermal history) that we believe there is

need for a long-term stability model. MANCEF will work with members to develop models for each of their transducers. This will involve working with each member's sensors measuring internal volume, hermetic-seal quality (possibly by helium-leak detection), outgassing of constituent materials, evaluation of getters and measurements of porosity of diaphragm, etc.

This program has started with the fractographic analysis of glass frit-silicon bonds. Further work will involve hermetic-seal tests before starting with "Modeling" and expanding activities to cover all members' absolute-pressure transducers

Micro-relays

Several companies are producing micro-relays. The reliability quotient for a relay is the number of switching operations and/or the period of time for which the "Closed" resistance remains below a specified value. Often, the contact resistance of a relay increases, and the relay "Fails," without showing any obvious degradation of the contact surfaces. Switching load and contact materials are obvious factors but the environmental gasses have also been found to play a significant role.

Electron and atomic-force microscopes may be used to undertake detailed topographical analysis of contact surfaces. SEM secondary electron spectroscopy can identify surface contaminants and chemical gas or mass-spectrographic analysis can be made of dissolved or scrapped off surface contaminants.

3.5.4. Accelerated life testing

Accelerated life testing is crucial in determining the long-term reliability of devices. With spacecraft life times in the decades and with automobile parts warranted for 100,000 miles and a decade, the operational lifetime of a device already exceeds its design and fabrication time many times over. Accelerated life testing is thus mandatory.

The principal problem with accelerated life testing is applying realistic stressing that correlates with the survivability and/or degradation of a device while not invoking extraneous failure mechanisms. Electrical diagnostic and screening tests, and in some cases trimming, are undertaken on the wafer as a first-level assurance qualification. Mechanical stimulus of a sensor's (effector's) measurement is not done until after dicing and packaging. Typically, mechanical burn-in is the second screening level for parts that have survived the mechanical

traumas of dicing, ultra-sonic bonding and packaging; possibly electrostatic trauma, and the shock (quiescent) of transport. The next screening level involves the systematic stressing of the transducer (an accelerometer for example) by voltage cycling, temperature cycling, drop testing and autoclave cycling.

The reliability assessment for the device is then determined by the analysis of failures and failure rates for each testing level. This quality assurance procedure is typical of the industry and universally recognized as inadequate.

A means of applying mechanical effectors stimulus directly and individually to each sensor on a wafer has been identified. Electrical and mechanical "Probing" can provide diagnostic testing, screening and infant-mortality discrimination before dicing and packaging. However, we believe the techniques are even more powerful in allowing direct measurement of each device's Young's modulus, bulk density and structural damping. Extensive mechanical burn-in (life testing) of transducers is also provided by operating the device at resonance for extended periods.

We believe that the industry will be easily convinced of the economics of additional pre-package screening and the potential of a rigorous "Accelerated Life Testing" technique. MANCEF will attempt to convince industrial members of the utility of funding the implementation of these techniques in their respective fabrication facilities. An accurate "Accelerated Life Testing" predictor of reliability is the "Holy Grail" for determining the technology readiness levels (TRLs) of micro aerospace components.

3.5.5. DNA chip characterization tools

The reliability of DNA chips is associated with accuracies related to image analysis, calibration, reproducibility, identifying co-regulated genes by cluster analysis, and detecting transcription-factor binding sites in clusters of co-regulated genes.

Fluorescence microscopy is primarily used for the characterization of chemically micro-structured surfaces since structures down to the low-µm range can be investigated (Institute for Physical High Technology, Jena, Germany). This is achieved by the direct reaction of tailored fluorescence dyes with functional groups on the surface, or by hybridization of fluorescence-labeled DNA with single-stranded complementary DNA on surfaces. The mainly covalent

binding of dyes, however, is usually not reversible and is just as time-consuming as hybridization. In contrast, it is possible to adsorb fluorescence dyes via noncovalent interactions on surfaces like hydrogen bonds, van-der-Waals interactions, dipole-dipole interactions or ionic interactions and hydrophilic/hydrophobic properties of the dyes and the surfaces. The affinity of the fluorescence dyes to the chemically patterned monomolecular surfaces on smooth silicon or glass substrates can be controlled by the choice of the solvent as well*(Source: Institute for Physical High Technology, Germany)*.

This non-destructive method is quick, irrespective of chip geometry. Since the adsorption of the molecules at the surface is reversible, the surfaces are available for further chemical modifications after characterization.

3.6. The Future

Intermediate levels of MEMS design abstraction are searched, keeping compatibility with IC design practice and with a cleaner separation between technological processing and design effort. This leverages research and development such as circuit simulation that makes also possible realistic fault modeling and design-for test, and the use of A-HDLs. In this way, test technology already developed for microelectronics can be used for addressing the testing of MEMS parts. The design and validation of highly complex systems such as mixed technology SoCs (Systems-on-a-Chip) could well be addressed this way (Mir, 2000).

3.7. MEMS Reliability Tool Kit

The tools required to conduct MEMS reliability studies are as follows:

1) Non-destructive/non-invasive tools to measure dynamic and static mechanical displacement
2) Automated test systems
3) Surface science and micro-analytical tools
4) Environmental chambers
5) Shock and vibration testers
6) Thermal cycling and thermal shock

Unlike ICs, MEMS devices move and thus special tools and techniques are required to measure mechanical motion on a nanometer scale in all 6 degrees of freedom, and on a time

scale faster than the device's resonance frequency. These tools are used to comprehend device behavior in detail so as to provide swift feedback to the designers to improve the reliability by design. The reliability tool kit has to measure minute changes in device behavior after accelerated testing (large number of cycles, mechanical shock, thermal cycling, etc.) to estimate the lifetime once the failure mechanisms have been identified.

3.7.1. Non-Destructive & Non-Invasive

1) Static measurements of MEMS: Optical surface profilometer.

The most common tool is an optical surface profilometer which generates a 3D map of the surface of a device with ~10 nm of vertical resolution that provides such information as the height of self-assembled structures, membrane curvature, micromirror tilt, cantilever deflection, roughness, finish and texture of surfaces etc.

2) Dynamic measurement of MEMS

Laser Doppler Vibrometry (LDV) is a non-contact sub-nanometer resolution vibration measurement technique using the Doppler effect. The LDV allows measurement of miniature, soft surfaces, even under water, and dynamical characterization of out-of-plane periodic motion of MEMS components without mass loading. MEMS devices can operate much faster than standard video cameras or interferometers can acquire data. Hence, stroboscopic techniques are used to "Freeze" the device at a given phase. The LDV measures only out-of-plane velocity. To measure all 6 degrees of motion, a combination of strobed interferometry (for out-of-plane motion) with strobed machine vision (for in-plane motion) is required. Umech's MicroVision MEMS Motion Analyzer is a commercially available tool combining 2D and 3D strobed measurement abilities.

3.7.2. Automated test systems

Sandia National Laboratories has developed SHiMMeR (Sandia High volume Measurement of Micromachine Reliability) to control and measure up to 256 MEMS parts simultaneously, while subjecting them to varying environmental conditions, to study their reliability, develop optimized drive strategies, and measure lifetime. SHiMMeR is a plexiglass enclosure with a high-powered optical microscope and a video camera that observes and records the failures of MEMS. The microscope and focused ion-beam images are used to determine where, when, and what causes MEMS to fail.

Texas Instruments developed the MirrorMaster, a custom optical inspection tool for DMD™ devices that inspects every pixel of a DMD array and determines the response of each pixel to different electrical drive signals. Etec, Inc., also offers an automated high-volume tool that addresses high-volume MEMS testing at both wafer and die level.

3.7.3. Surface-science characterization tools

MEMS reliability issues more often than not are intrinsically related to material science issues. To understand failure modes, an excellent understanding of the morphology and composition of the films that make up the device is required. This entails the need for many of the analytical instruments typically found in the IC industry: SEMs, TEMs, AFMs, Auger spectroscopy, FIBs, RBS (Rutherford Backscattering Spectrometry), etc. These tools provide data regarding diffusion barrier effectiveness, Self-Assembled Monolayer (SAM) anti-stiction coating uniformity, and extent-of-wear damage, etc. In addition, time of flight SIMS and XPS have value in identifying contamination and the efficacy of various cleaning procedures.

3.7.4. Environmental chambers

Temperature and relative humidity are very important accelerating factors for several failure modes. Hence it is essential to be able to operate MEMS devices under controlled temperature and humidity. Some commercial chambers may require modifications because the testing of MEMS differs from standard IC testing. For example, one may wish to measure the reflectivity of a micromirror, or use an optical technique to measure the resonant frequency of an actuator while the device is under a controlled ambient (this can require long-working-distance microscopes, optical access ports, etc.)

3.7.5. Shock and vibration

MEMS may be perceived as mechanically fragile and susceptible to mechanical shock, so there is a special need to test them under severe shocks to build customer confidence. A typical commercial shock tester can provide up to ~1000 gs. Lucent's Bell Laboratories uses a special tester to shock mirrors at over 25,000 gs in 3 translation and 3 rotational directions/axes. The standard equipment for mechanical vibration testing is a shaker table to control the amplitude and frequency of vibration. There is a range of possible typical vibrations: earthquake, office vibration, vibration in a car, vibration during a rocket launch, to name a few.

3.7.6. Thermal cycling and shock

Temperature cycling (ramping the temperature up and down), and temperature shock (rapid change of temperature) are important elements of a complete reliability test plan. Thermal cycling and thermal shock can affect crack growth, delaminations, outgassing, die-attach failure, reflector flatness, wafer bonding, and most importantly package hermeticity.

The MEMS tool kit continues to grow and commercial tools aimed at testing MEMS devices, on a wafer, chip, and at the package level are getting popular. Specialized tools not found in an IC test lab are required because MEMS devices have moving parts and exhibit failure modes not found in the IC realm.

4.0 Predictive Modeling

Predictive modeling (Hartzell, 1999) is the expert application of the knowledge gained in short-term accelerated testing to the general use conditions of the field part. A methodology for predicting the expected field failure rate of an atypical population with a known defect and failure mechanism is described. The expected failure rate is based on empirically derived accelerated failure rates applied to the expected use conditions of the device. A case study of prediction failures that occur in MEMS-based accelerometers is presented.

4.1. Description of Case Study

The Analog Devices accelerometer is an integrated surface micromachined sensor with on-chip electronic circuitry. The sensor consists of a set of fixed beams and a moveable structure, which contains a center mass with attached beams. The output voltage of the sensor is a function of the air-gap capacitance between the fixed and moveable beams. Upon exposure to an applied acceleration in the x-axis of the sensor, movement of the center mass and beams create a change in the device output that is proportional to the acceleration. Full displacement of the gap is achieved (beams will contact each other) as a result of a large x-axis mechanical acceleration that exceeds the designed use conditions of the sensor. The center mass will return to its resting position if the x-axis restoring force (a function of the spring constant of the sensor) can overcome the beam-surface adhesive forces. These adhesive forces are complex; under applied power, electrostatic forces are present due to the work-function differential between the surfaces. Once the beams are approximately 20-nm apart, van der Waals forces come into play

(Maboudian, 1997). If upon beam-to-beam contact, the surface adhesive forces exceed the beams' x-axis mechanical restoring force, a phenomenon called lateral stiction occurs. Here, the center mass does not return to its resting position so the sensor is rendered nonfunctional. Electrostatic forces are a function of applied voltage, the gap distance, and the air-gap permittivity. Van der Waals forces are a function of the distance between the beams, Hamaker's constant, surface roughness, etc.

Electrostatic and van der Waals forces can act between the center mass and the sensor substrate (ground plane) as well, resulting in vertical stiction. A sufficiently strong z-axis shock will collapse the structure and inhibit recovery if the z-axis restoring force of the sensor does not exceed the adhesive forces between the contacting surfaces. The population of accelerometer devices in this study had a known fabrication defect that made the devices prone to z-axis stiction. The number of affected devices was known, which made this population ideal for a predictive study. This fabrication defect resulted in a distribution of reduced spacing between the center mass and the sensor substrate.

Predictive modeling helps identify the portion of the population which had the spacing reduced sufficiently to result in vertical stiction. It also determines the probability of vertical stiction as a function of applied powered g-level shock.

Figure 6 presents the empirically derived single-shock survival data for the given population. The probability of survival is presented as a function of the applied shock level normalized to gravity (g's). The trend indicates a decreasing survival rate with increasing shock level. A second-order polynomial with a fixed intercept of 1 was reasonably fit ($R^2 = 0.80$) to the single-shock survival data and is also presented within Figure 6.

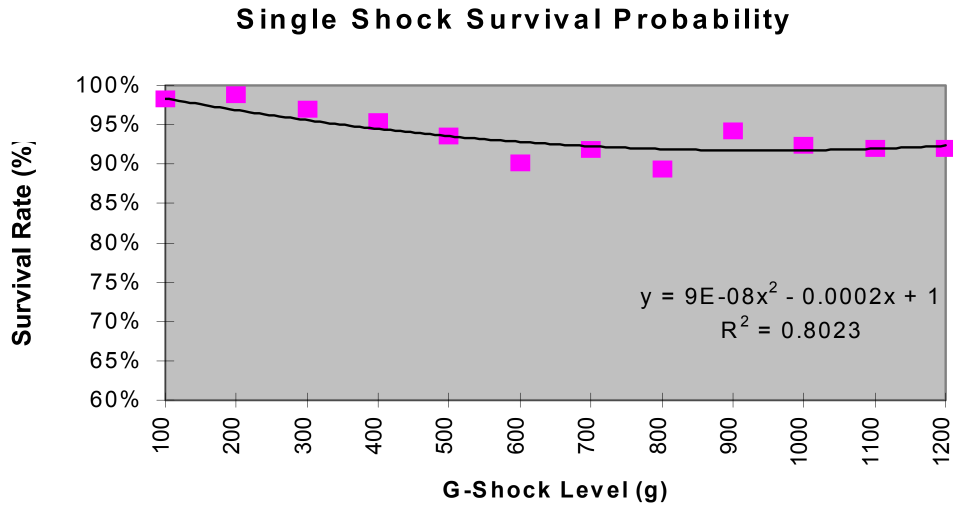

Figure 6. Probability of Survival versus Applied Shock (Hartzell, 1999).

4.2. Application of Model

The expected behavior of the affected population was described in the previous section and follows the general form of the equation:

$$F = q_f P_f \{G_z(t)\}$$

where:

F= the number of estimated accelerometer device failures;

q_f = the quantity of stiction-susceptible parts out of the entire population of parts to be analyzed, $P_f \{G_z(t)\}$ is a probability distribution function empirically developed using the procedures described herein on known stiction-prone parts (note that P_f is 1 minus the survival rate, P_s, shown in Fig. 6);

and $\{G_z(t)\}$ is the z-axis lifetime shock profile that the accelerometer is estimated to experience.

Predicting the expected failure rate P_f is dependent on the expected z-axis shock profile, which is end-user application specific. Based on the application, design requirements and known use conditions, a reasonable-lifetime z-axis shock profile can be assumed. For example, one application might expect to receive five shocks of varying levels over the designed 10-year life

of the system. Each individual shock is applied to the empirically derived single-shock survival model to determine the probability of surviving each event.

Once each event survival probability is determined, the overall survival rate is simply calculated as the multiple of each event. For this example the overall survival rate would equal:

$$P_f\{G_z(t)\} = 1 - Ps\{G_z(t)\}$$

Since $Ps\{G_z(t)\}$ is the probability of survival of n sequential shocks, $P_f\{G_z(t)\}$ is expressed below as:

$P_f\{G_z(t)\} = 1 - [\,Ps\{100g\} \text{ x } Ps\{200g\} \text{ x } Ps\{300g\} \text{ x } Ps\{400g\} \text{ x } Ps\{500g\}\,]$

$P_f\{G_z(t)\} = 1 - \{(0.9809) \text{ x } (0.9636) \text{ x } (0.9481) \text{ x } (0.9344) \text{ x } (0.9225)\}$ (From Figure 6)

Therefore,

$P_f\{G_z(t)\} = 0.2275$

Determining the expected quantity in the field that will fail over the life of the part becomes the application of the expected failure rate to the known affected population. The determination of q_f, is as follows:

The quantity of stiction susceptible parts is performed through an electromechanical screen. Not all parts in the population were affected by the defect, which could result in z-axis failure, thus running the whole population through the screen results in identifying the most stiction-susceptible devices. The shock imparted by the electromechanical screen is in excess of the part datasheet limits and is applied directly to the device package in the z-direction, resulting in beam collapse to the substrate. The mechanical stimulus is applied directly to the packaged sensor, while the sensor is under power and mounted in a rigid socket fixture. The high-frequency mechanical pulse is applied five times; the sensor is electrically sampled for functionality prior to imparting the pulse, and after each pulse application. This extreme test will result in stiction failure (output signal out of range) if the part has the level of fabrication defect, which makes it stiction-susceptible. The known affected population, in this case has been determined to be q_f =

130. Applying this methodology, the expected quantity that will fail due to this mechanism and application is:

$$F = q_f P_f \{G_z(t)\}$$

$$F = 130\,(0.2275)$$

F = 29

5.0 Statistical Characterization

5.1. Importance of Reliability Statistics

By definition, reliability is a probabilistic concept and therefore statistical methods are very useful. Reliability statistics are important because they help:

1) Identify the correct model to determine the average time to failure, and the width of the distributions.
2) Understand the distribution of failures; several failure modes, several populations.
3) Extrapolate from accelerated testing to standard operating conditions.
4) Determine the optimum burn-in conditions. Excessive burn-in can lower the yield and shorten the device life by increasing wearout failures.

5.2. Reliability Models

Reliability models are used to select high-temperature packaging materials systems for optimal performance and lifetime. They are also used to optimize candidate material selection. The material properties, especially, metal/metal and metal/ceramic interfaces, of packaging elements will be modeled to select materials for optimized performance/functionality and lifetime under a variety of harsh environmental conditions such as high-temperature and thermal cycling.

The three standard probability models (Figure 7 and Table 7) used in MEMS reliability modeling are:

- Exponential
- Weibull
- Log normal

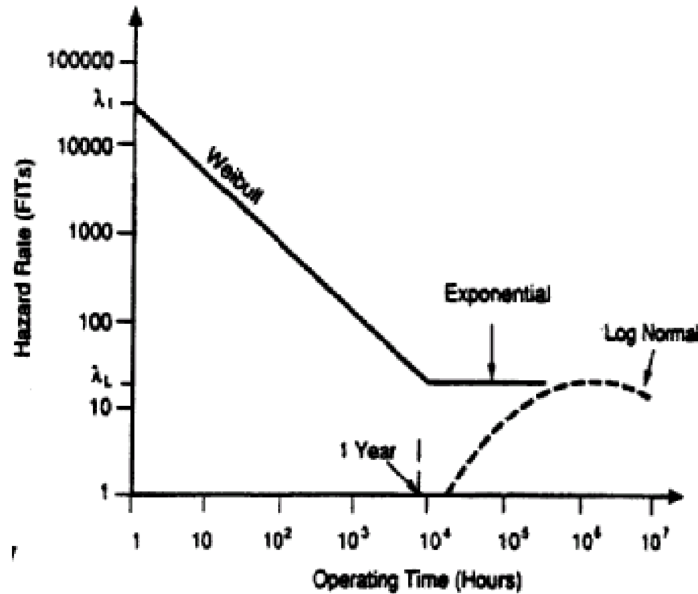

Figure 7. The Three Standard Models used in MEMS Reliability Modeling. FIT (Failure in Time) refers to the number of devices failed in 10^9 hours.

Different models apply in different cases (or not at all), and it takes a lot of data to be able to determine which gives the best fit. The mathematical equations used to derive these models are not explained but the relative advantages and disadvantages are explained. A complete description of these standard reliability models can be found in standard reliability references (see for example, Kececioglu).

Table 7. A Comparison of Standard MEMS Reliability Models

Model	Applications	Advantages	Disadvantages
Exponential	Failures are due to human error	Simplest	Cannot account for wearout
Weibull	Infant mortality Failure forecasting Evaluating corrective action	Small sample requirement thus reduces testing cost	Cannot account for wearout
Log normal	To model long-term failures and wearout	Can be derived by assumptions matching many semiconductor failure mechanisms; hence best among the three	None notable

5.3. Accelerated Testing

It is essential to set up a careful accelerated test plan early because “The options of waiting, until every last issue that might affect reliability is unambiguously resolved, does not exist” (Nash, 1993). The crucial assumption in accelerated testing is that the mechanism of damage is the same under normal and accelerated test conditions. The Acceleration Factor (AF) is defined as a constant derived from experimental data, which relates the times to failure at two different stresses. The accelerating stress could be (singly or in combination) temperature, voltage, current, relative humidity, strain, vibration, laser power, etc. If temperature is used, an Arrhenius law is almost always assumed. The AF allows extrapolation of failure rates from accelerated test conditions to use conditions according to the equation:

$$\mathrm{AF}=\exp\left[\frac{E}{k_B}\left(\frac{1}{T_1}-\frac{1}{T_2}\right)+\mathrm{Const}\cdot\left(V_2-V_1\right)\right]$$

where

E = thermal activation energy (eV); a value that depends on the failure mechanism (silicon defects range from 0.3-0.5eV and contamination is 1.0 eV, etc.)

k_B = Boltzmann’s Constant (8.63 x 10^{-5} eV/K)

T_1 = the use temperature (Kelvin)

T_2 = life-test stress temperature (Kelvin)

Once the AF has been determined for one or more parameters, the device MTTF (Mean Time To Failure) under normal operating conditions can be determined. An AF greater than 10 should be treated cautiously since it is unlikely that the same failure mechanism is still dominant. AFs much larger than ten should be ignored.

5.4. MTTF (Mean Time to Failure)

MTTF is the time where 63.2% of the population has failed. The MTTF is not the anticipated life, because by MTTF, approximately 50% of the devices have already failed. The deciding factor on adopting materials, new processing and packaging techniques in the MEMS industry is the MTTF. Commercialization of a MEMS-based Pressure Mass-Flow Controller (PMFC) and its use in various application realms received a thrust when it was proved that single-crystal

silicon has an excellent MTTF when used as the mechanical material of the PMFC. One of the reasons the PMFC is preferred to the Thermal Mass Flow Controller (TMFC) in applications like control of gases during semiconductor processing, is due to a higher MTTF.

6.0 Properties of Manufacturing Materials

6.1. Existing Materials

While many of the mechanical properties of MEMS/MST materials are well known in their macro and bulk-machined forms, their properties at micro and nano-scale surface machined forms are different and often unknown. Furthermore, the decreasing geometry of MEMS/MST structures increases the relative importance of the surface properties (surface physics) verses the volumetric properties of materials. The microstructure and micro-morphology of the structure such as grain size, inter-atomic bonds and crystalline boundaries of a material are the dominant parameters determining mechanical properties.

The pioneers of micromachining recognized the importance of systematic characterization of mechanical properties of MEMS/MST materials. Each investigator built devices, based on test results, iteratively tuned the design to obtain requisite performance. The development of new MEMS/MST devices has been stretched considerably and many of the designs have failed because of ignorance about actual material properties.

Considering silicon, mechanical performance and fracture stress are related to fabrication techniques such as crystal growth from a high-temperature melt, epitaxial growth or sputtered deposition. The mechanical properties of silicon and related dielectrics (silicon-dioxide, silicon-nitride) provide a relatively robust materials system in which to build IC-compatible MEMS devices. The dimensions and design of modern MEMS devices can result in high-stiffness (k) and low-mass (m) mechanically robust devices. Thus resonant frequency and vibration or shock sensitivity of a device is proportional to the ratio k/m. Silicon-based MEMS fabrication techniques, device design parameters, operational modes, and packaging can be simultaneously optimized to afford the lowest possible materials defect density, stresses and stress gradients, and CTE (Coefficient of Thermal Expansion) mismatch in multi-material MEMS devices. This optimization can eliminate the occurrence of crack initiation and propagation, fatigue-related fracture, or mass transfer through glide and diffusion mechanisms.

With compounds and polymers, mechanical properties are strong functions of deposition conditions and frequently of processes that both proceed and follow deposition. Frequently, MEMS/MST devices are created from multi-layered structures of multiple materials where each material has a different CTE resulting in room-temperature stress that is a function of the fabricating process temperatures. There are also an increasing number of MEMS/MST devices created from electro-deposited metals where the physical properties and residual stress are again a function of deposition conditions.

With each individual foundry having its own particular materials and with the increasing numbers of processes involved in fabricating MEMS/MST, and particularly surfaced machined MEMS/MST, the task of creating a comprehensive transferable materials properties catalogue is immense. In a rapidly evolving technology, there is also difficulty in identifying which process combinations are going to be prevalent in the next five years.

Traditionally, foundries have built devices, and based on performance, iteratively tuned the design and jealously guarded the "Properties" information from potential competitors. The industry would greatly benefit from a transferable material properties catalogue. MANCEF will approach DARPA, NIST, SEMI and VLSI Standards seeking support for the daunting task of creating a materials properties database. NASA has already compiled and maintains an extensive database on material outgassing (*http://misspiggy.gsfc.nasa.gov/og/*). MANCEF will participate in disseminating this information.

MANCEF will detail the mechanical measuring techniques and micro test structures that will enable the characterization, both individually and collectively, of materials used in fabricating a MEMS/MST device directly on the wafer measurements. The technique will also enable the determination of material properties at different stages of fabrication, a powerful diagnostic tool. The wafer test structures and mechanical measuring techniques will enable the generation of a materials database for a particular foundry and process. MANCEF would then encourage members to pool their databases and research anomalies, and make decisions on the utility of filling in any "Gaps" in the database.

6.2. MEMS/MST Quality and Reliability Handbook

In addition to the properties of manufacturing materials, MANCEF has general consensus on the need for a MEMS/MST Quality and Reliability Handbook. The content of the handbook is

intended to cover the spectrum of technologies and practices that the MEMS/MST production engineer needs to be familiar with: from processing definitions to statistical process control; from the physics of MEMS/MST and structural components to the monitoring of incoming materials; from wafer processing to packaging; and from the testing of prototypes and production devices to the determination of reliability.

Members are committed to submitting material for relevant topics and MANCEF will take the responsibility for coordinating the activities and subsequently editing the handbook. As with material properties, DARPA, NIST, SEMI and VLSI Standards will be approached for support in undertaking this activity.

6.3. Stress-Free Polysilicon

Polysilicon is a popular IC-compatible MEMS material. The manufacture of stress-free polysilicon results in robust and long-lasting MEMS devices. A silicon-based surface micromachined MEMs process typically combines freestanding polysilicon structures capable of motion with traditional integrated circuitry. This union has many advantages and many real-world applications; however, the industry expectation of part reliability of this new technology is expected to be at the same level as traditional integrated circuitry. Polysilicon is usually deposited by low-pressure chemical vapor deposition (LPCVD) using thermal decomposition of silane (SiH_4). However, this process generally produces as-deposited films with high residual stresses and residual stress gradients through the film thickness, which can be detrimental to MEMS devices.

Residual stress significantly affects engineering properties of structural components, like fatigue life, dimensional stability, and corrosion resistance. The residual stresses and residual stress gradients must be controlled, and often eliminated, to achieve optimum device performance. Thus residual stress analysis is required in the design of surface micomachined devices and in the estimation of their reliability under real service conditions.

Polysilicon films, deposited by LPCVD, exhibit tensile or compressive residual stresses, depending on the deposition temperature. Researchers have tried multilayers of polysilicon, silicon-dioxide, and silicon-nitride in different combinations, to minimize stress in a membrane. Capacitive pressure sensors have been fabricated with stress-compensated membranes formed by depositing a compressive CVD SiO_2 film onto a boron-doped silicon membrane containing

tensile stresses; microheating stages have been fabricated using $SiO_2/Si_xN_y/SiO_2$ membranes; and Fabry–Perot cavity-based sensors have been fabricated using $Si_xN_y/SiO_2/Si_xN_y$ diaphragms. But any multilayer composed of dissimilar materials will suffer from thermal strains due to different thermal expansion coefficients of the several materials. This will create stress gradients and could deform structures if the temperature changes during device operation. Hence, the probability of this technique being adopted by MEMS manufacturers is low.

High-temperature annealing and high-temperature deposition have been used to produce low-stress polysilicon films in the industry. In the future, manufacturers will be pressured to avoid any high-temperature processing, since future MEMS devices will have to include densely populated thermally sensitive ICs and micro-mechanical devices on the same substrate.

Multilayers of polysilicon, deposited at varying temperatures at or below $615^{o}C$, individually possess residual stresses but of opposite sign, and when combined into multilayer films display overall near-zero stresses and near-zero stress gradients (Figure 8). In the next 5 years, the MultiPoly ™ process described above or a similar process will be used by the MEMS industry to achieve better reliability for its products. This technique to achieve zero-stress LPCVD polysilicon films was developed by alternate deposition of compressive and tensile layers. This technique has many advantages over other techniques used to achieve low residual stresses in thin films, viz. smoother surfaces, reduced thermal strains, and no CMP requirement that is expensive and time-consuming.

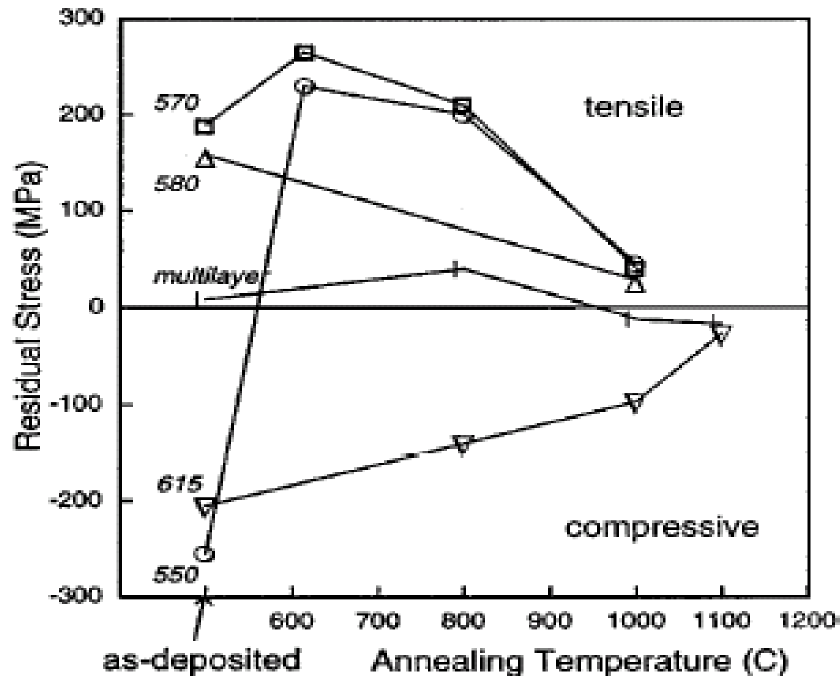

Figure 8. Residual Stresses of Various Polysilicon Films as Deposited and after Annealing for 30 Minutes in Nitrogen. The Single-layer Films are labeled by their Deposition Temperatures. (Yang, 2000).

As seen in Figure 8, the overall residual stress of the MultiPoly ™ film is near zero (8 MPa) as deposited. The stresses and stress gradients can be made lower (0-0.2MPA/µm) by depositing additional polysilicon layers.

6.4. Reliability Issues of New Materials

Fatigue is one of the most severe failure mechanisms of macroscopic metallic components in many technological applications such as trains or aircraft. At present, however, the role of fatigue for the reliability of microsystems has not yet been explored in detail. This is probably due to the fact that most MEMS devices are based on silicon in which fatigue is not expected to be a problem. However, the introduction of metallic components in such systems can make them vulnerable to fatigue failure as devices are often stressed under cyclic conditions

LIGA is a relatively new MEMS technology and has introduced non-IC compatible materials. The U.S. Navy is developing LIGA-based microactuators for use in ordnance safety and arming devices. The implementation of LIGA mechanisms in similar high-reliability systems requires a complete assessment of the strength and aging properties of electrodeposited material like Ni-Fe alloys which are favored in MEMS because of their superior soft magnetic properties

and high strength. However, they are somewhat difficult to electrodeposit to thicknesses greater than ~50 μms because of residual stress present in the growing film. In this process, stress reduction is achieved by including saccharin in the electrolyte. Sulfur migration at grain boundaries is usually responsible for embrittlement of Ni-Fe alloys during thermal exposures and care should be taken to avoid exposure to sulfur to ensure high reliability (Janek, 2001).

Sandia National Laboratories has developed a novel plasma-enhanced CVD (PECVD) process to obtain conformal friction-reducing coatings for LIGA MEMS. A 100-nm-thick commercial PECVD diamond like nanocomposite (DLN) was coated on a LIGA wafer with MEMS elements on it. The coated wafer was back-sputtered to remove the coating material from the planar surfaces of the MEMS elements and from the rest of the wafer. This technique can be easily adapted to apply a variety of other friction-reducing coatings for improved performance and reliability of LIGA microsystems.

7.0 Design for Reliability

7.1. Improving Reliability

To ensure built-in reliability, MEMS reliability research has a fourfold mission:

1) To obtain a fundamental understanding of chip-level, MEMS-specific failure mechanisms.
2) To facilitate the design, packaging, manufacturability, and testing of commercially interesting MEMS research and development concepts.
3) To preview compliance and qualification testing of MEMS devices.
4) To ensure the long-term reliability of MEMS products in the field.

Commercial applications of MEMS that mandate rapid introduction into the marketplace can benefit from such a built-in reliability paradigm. Specifically, an interdependent relationship and a tight feedback loop between all contributors to device, subsystem, and system design, fabrication, manufacturing and testing, reliability physics, and packaging, can greatly accelerate the time-to-market of emerging MEMS products (Figure 9).

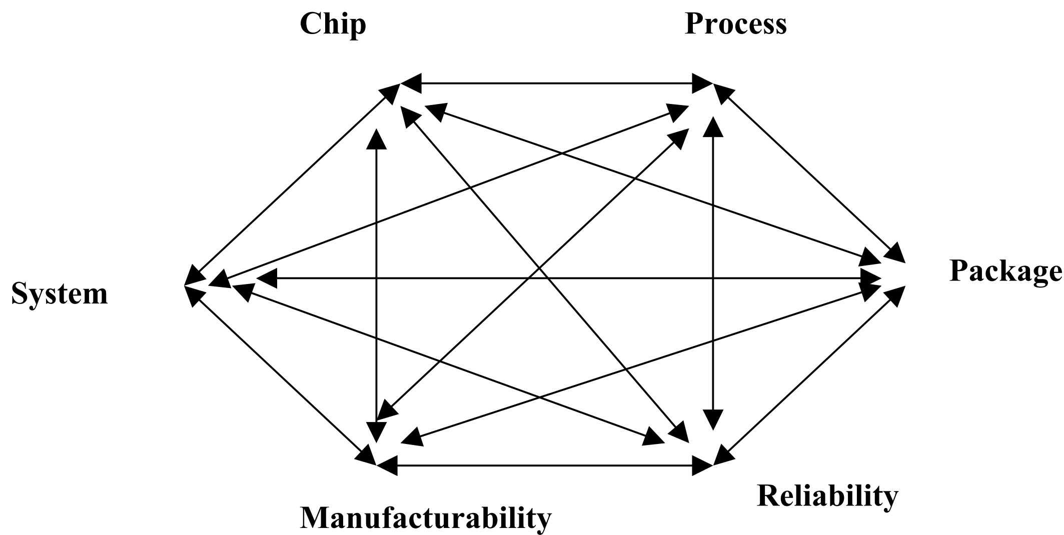

Figure 9. Graphic Representation of a Built-in Reliability Paradigm Based on Interdependent MEMS Product-development Activities.

Classic reliability-physics methodology, as applicable to MEMS, begins with a mutual test plan designed to reveal failure modes or failure mechanisms through the application of a series of, for example, thermal, electrical, mechanical, and optical environmental applied conditions. A fundamental understanding of each observed failure mode or mechanism is then sought. Experiments are designed to identify and isolate each mechanism, and to determine its fundamental physical characteristics, root cause, and statistical distribution.

Accelerating factors for each mechanism are then identified to permit more rapid (i.e., time-efficient) experimentation. "Over-stressing" strategies for accelerating the failure of the devices relative to nominal operating conditions, will depend on device design, materials choices, and intended operating conditions (Nelson, 1990). The most straightforward accelerated test design results in a single failure mode, whose characteristics represent nominal operating and environmental conditions, facilitate extrapolation and prediction of lifetimes. The most widely known and conceptually simple graphic representation of reliability concepts is known as the bathtub curve (Figure 10). The relative contributions of infant mortality, external events, and wear-out phenomena are modeled as independent and additive to obtain the characteristic bathtub-shaped curve of hazard rate versus time.

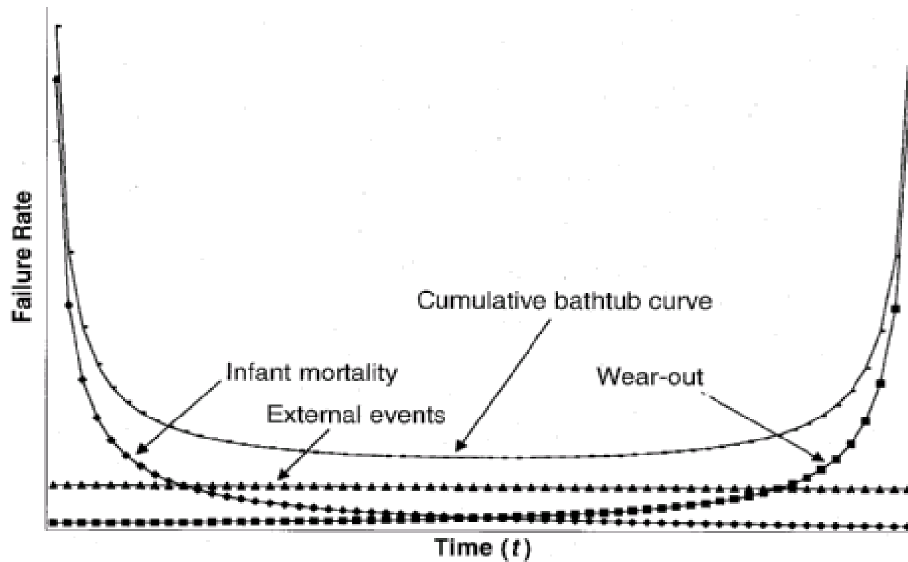

Figure 10. Graphic Representation of a Reliability Concept Known as the Bathtub Curve, Showing Hazard Rate versus Time. The Relative Contributions of Infant Mortality, External Events, and Wear-out, are Modeled as Independent and Additive. (Nash, 1993; Ohring, 1998)

Infant mortality in MEMS devices is visualized as an initially high, rapidly diminishing hazard rate. It is assumed to derive primarily from non-uniformity and unpredictable or unobserved discrepancies in manufacture. Infant mortality may result from missing or poorly formed structural elements, wiring, or electrodes; surface or bulk contamination; scratches; bridging; particulates; stringers; incomplete hermetic seals; and similar fabrication or packaging-induced phenomena. Infant mortality can be greatly reduced by burn-in or screening techniques at the MEMS manufacturer, before the devices reach the consumer. After the initially high rate of infant-mortality failures has diminished, a relatively small, time-independent failure-rate characteristic persists that is termed the useful life. It is attributed to random occurring defects, including effects such as: contamination, ionic surface charging, random material defects, etc.

Wear-out is conceptualized as a sudden rapid increase in the failure rate after a period of useful product life. Wear-out of MEMS might result from creep (e.g., in metals and polymers); fatigue; formation and propagation of microcracks; interdiffusion (e.g., in metals and semiconductor junctions); compromised barrier layers (e.g., metallization); plasma-induced surface damage; outgassing, moisture uptake or creeping of epoxy die-attach materials; dielectric breakdown; corrosion; and many other mechanisms. The wear-out mechanisms characteristic of a given MEMS product are specific to the chosen materials system, fabrication techniques, design, packaging, and operating conditions. Wear-out mechanisms are presumed to be present

in, and to eventually cause the failure of, every device. However, built-in reliability that prevents failure due to wear-out during the intended service life is both possible and normative. This provides the motivation for reliability-physics investigations that iteratively identify the "Weak Links" (or the most dominant infant mortality or wear-out mechanisms) in a given technology, device, or product, then redesign the technology or product based on the understanding gained.

Exponential, lognormal, and Weibull distributions are variously used to predict lifetimes based on experimental results. Failures in 10^9 hours, known as FITs or FIT rates, are used as a metric for comparing test populations. For example, 1 FIT is equivalent to 1 failure in 10^6 devices in 1000 hours, or 1 failure in 10^5 devices in 10,000 hours. The advantageous statistics of high-volume manufacturing are readily apparent when estimating FITs. Deterministic and predictive methods of MEMS reliability investigation based on failure-mechanism modeling are considered alternatives to large-volume statistical reliability studies.

7.2. Enhancing the Reliability of Surface Micromachined Devices

Stiction can occur during the release process or afterward.

Methods to avoid stiction are:

1) Mechanisms along the vertical direction are made such that they are not easily bent.
2) Minimize the overlapping surface area between flat parts by using dimples. Dimples reduce the contact area by more than a factor of a 1000 if a 2-μm x 2-μm dimple is used every 75 μm.
3) Use large cutouts in gears and other structures. In most cases, a surface-micromachined gear does not need the stiffness provided by the material between the teeth and the hub.
4) Limitations of the fabrication and packaging process must be known and should not be violated by the MEMS designer.

Designers must be able to predict problems that might occur during the fabrication process and ensure that their designs will still work in spite of the problems. For example, a release process with an abundance of conductive particles is not compatible with designs that employ electrostatic comb drives because the particles may become lodged between the comb fingers and short them together. Thermal actuators over a nonconductive substrate would be a better

alternative. Also, a non-hermetic packaging process would not be compatible with devices that are susceptible to humidity-induced stiction.

8.0 MEMS and Metrology

MEMS metrology refers to the measurement and calibration of physical dimensions of microsystems and microstructures using special measurements systems or instruments.

The dimension of microstructures that are measured include line widths, film thickness, surface structure and roughness, step heights, particle size, atomic composition, defect inspections, etc.

8.1. MEMS Metrology Tools

The tools used in MEMS metrology include:

- Optical microscopy
- Scanning-electron microscopy (SEM)
- Atomic-force microscopy (AFM)
- Scanning tunneling microscopy (STM)
- Near- field microscopy
- Laser/white-light interferometry
- Video microscopy
- Surface profilers
- Roughness testers
- Ellipsometry

Easy access to MEMS-specific wafer-processing equipment is a major factor that will help MEMS commercialization. These tools require new metrology methods and equipment to provide invaluable process feedback. These metrology tools support not only fundamental R&D, but also high-volume production of silicon micromachined products.

Three areas of metrology of particular interest to MEMS device fabrication are discussed below (Clair, 2000).

1. Surface roughness:

This has a major influence on the quality of silicon direct wafer-bonding processes. An optical profiler in the phase-shifting interferometry mode, can be used to measure surface roughness R_a. A R_a between 0.5-1 indicates that the wafer is likely to bond well in subsequent MEMS processing. DARPA envisions constructing a network of computer microvision test stations between research institutions to enhance the metrology of MEMS.

2. Deflection measurement:

Evaluating film stresses in surface micromachined devices usually requires accurate measurement of the curvature of long, thin beams of polysilicon—the greater the beam curvature, the greater the intrinsic film stress due to stress gradients. Because contact during measurement would tend to deflect the beams, measurements are made using non-contact methods such as optical profilometry or interferometry.

3. Step-height measurement:

High-aspect-ratio microstructures formed by these processes have proven particularly difficult to measure by conventional methods. Such micromachined structures often exceed 100 μm in height, with narrowly spaced gaps between them. Optical profiling is used as it is ideally suited for measuring this range of step heights. Optical profiling systems are calibrated to certified step-height standards of standards organizations like NIST, for linearity over a 1-mm scan range to within ±0.5%. To verify the accuracy of the measurements, the results are compared to those of a stylus profiler.

At present, instrumentation and its associated GUI-based software are available for sensor calibration, motion analysis, wafer motion control, non-contact laser probing, 2D-3D data analysis and video imaging of both IC and non-IC-compatible MEMS.

Microsystems Technology Laboratories of MIT plans to develop a computer microvision for inexpensive *in situ* visualization and measurement of the motions of MEMS. It combines light microscopy, video imaging, and machine vision to enable remote metrology for MEMS. Images of MEMS are magnified with a microscope and projected onto a CCD camera. Stroboscopic illumination is used to take temporal sequences of images at multiple planes of focus that are studied later. The MEMS industry is expected to adopt remote metrology techniques that involve computer microvision by the start of the next decade. The measurement of important geometrical

parameters such as feature dimensions and thicknesses of air gaps using tools like interferometric computer microvision is very significant. This will help create a design/simulate/metrology loop to improve simulation tools for MEMS.

8.2. Calibration

Metrology can also be defined as the development and evaluation of calibration systems that measure characteristics of objects, materials or phenomena, such as length, mass, time, temperature, electric current etc. Calibration is simply the comparison of instrument performance to a standard of known accuracy. Calibration of MEMS devices is still in its formative stage.

Temperature calibration of micromachined integrated chemical sensors supported by finite-element simulation has proven to be feasible and reliable, but not many manufacturers implement them. Analog Devices temperature-calibrates its accelerometers to improve their overall accuracy.

9.0 Challenges in Packaging Reliability

9.1. Overview

An electronic package serves two primary purposes. It provides both support and protection to the components, which make up the electronic circuit. It must also allow for input and output of electrical signals. In certain cases, such as photodiodes, packaging may also be required to provide an access path for other stimulus types such as optical, acoustic, pressure, etc.

There is considerable overlap between reliability aspects for MEMS and packaging, like thermomechanical problems, requirement of materials know-how, and the same reliability methodology adopted, etc. The access of stimulus takes on added importance and complexity during the packaging of MEMS/MST devices like sensors. MEMS/MST sensors have been made, which run the gambit of sensing capabilities including electromagnetic (across the entire optical spectrum from ultraviolet to IR up to 20 μm), acoustic, pressure, temperature, vibration, magnetic and many more. In each case, once the device is designed and fabrication techniques are developed, the packaging becomes a separate problem unique to the specific device.

Ordinary microelectronic devices require extreme standards of cleanliness during fabrication. After fabrication is complete, cleanliness standards required for packaging are typically far less

critical. Only gross contaminants, which might short a circuit, lead to corrosive reactions, or in some other manner interfere with the functioning of the circuit, are considered a problem. Cleanliness requirements for MEMS/MST devices in packaging present a far more stringent set of requirements.

Because a MEMS/MST device has moving parts on a microscopic scale, consideration must be given to the size of a contaminant that would interfere with the motion of the various components of the device. A small piece of dust or fragment of bonding wire less than 1 μm in length and diameter will, if in a critical spot, completely prevent the operation of a MEMS/MST device. Worse yet, it may initially allow operation, but later move under environmental stresses so that the device develops a failure.

To increase the reliability of these and other MEMS/MST devices, JPL is studying the use of novel techniques for the detection of various types of contaminants and other imperfections. In the case of contaminants, the usefulness of X-ray microimaging has been demonstrated for detecting contaminants trapped between the moving segments of the MEMS/MST device. With proper use, the technique can also detect cracks and other defects in the device, which are invisible to optical microscopy.

A final method for improving the reliability of surface-micromachined mechanisms is to design with regard to the packaging of the MEMS device. A package that protects the surface-micromachined mechanism from particles, humidity and handling can also generate problems such as the outgassing of water vapor from the die-attach adhesive. MEMS devices have to be designed with regard to the final package or the packaging process.

Since many MEMS/MST devices are formed from multiple components that are bonded together, another consideration is how to detect the completeness of the bond. Here, acoustic microscopy techniques have been found to be useful. These techniques can also show irregularities in thin layers that would otherwise be undetectable. The need for MEMS devices to be stable at extreme environmental and radiation conditions will dominate in the next 5 years since this has a direct effect on the longevity of the device.

9.2. Hermetic Packaging

Hermetic packaging is a requirement for most MEMS applications since it protects devices from hostile external environments and from contaminants, ensuring long lifetimes and better performance. Until recently, a common method of packaging was to encapsulate the MEMS device in a capsule and bond it to a MEMS substrate. This cheap and flexible technique fell out of favor since high temperatures, which could have a deleterious effect on the electronics of the MEMS device, were required to ensure a good bond.

Hermetic MEMS packages are usually subjected to two kinds of tests:

1) A gross-leak check in IPA (isopropanol alcohol)
2) An accelerated test in an autoclave under 3 atm, 100% RH, and 128^{0}C

Since IPA has better wetability than water, it can more easily penetrate small openings, and is more suitable for a gross-leak check. Based on visual observation, it can be verified whether or not IPA penetrates the package bonding region. The gross IPA leak check is useful in screening devices for the accelerated test. Accelerated testing is then performed in an autoclave on devices that passed the IPA immersion test (Cheng, 2001). The fine leak test is considered inadequate to ensure hermiticity in MST because the detectable leak rate with this test is not compatible with the low volume MST.

Glass is generally chosen as a protection cap for hermetic packaging because it is mechanically robust, chemically stable, and transparent to light and RF signals which is desirable for biological or optical MEMS applications. A metal solder of 1-µm width, can effectively block moisture for over 8-12 years. A hermetic package based on localized aluminum/silicon-to-glass bonding that would have the advantages of both glass and metal solder was successfully demonstrated recently. The formation of aluminum oxide with a silicon precipitate composite layer is believed to be the source of the strong bond achieved. The bonding yield and reliability have been improved by increasing bonding time and applied pressure. The tests conducted to improve the reliability and hermeticity of the package using Weibull distribution is described since it is a common statistical theory to calculate the mean time to failure (MTTF) of packages.

The test results of a novel MEMS packaging technique, aluminum/silicon-to-glass hermetic packaging, were statistically described by the Weibull distribution function represented by:

$$F(t) = 1\text{-Exp}\left[-(t/\lambda)\right]^{\beta}$$

where

F (t) = the cumulative distribution function (cdf),

t = time,

β = s the shape factor and

λ = the characteristic lifetime or the mean time to failure (MTTF).

According to 11 package tests of the second set which are fabricated under improved conditions, 700ºC and 0.2 Mpa for 7.5 minutes, it is found that the MTTF of 11 glass–silicon packages is about 170 hours and the shape factor is about 0.66 (Cheng, 2001). A shape factor less than 1 indicates some defects that cause device failure already exist during package fabrication, like an unbonded region or unobservable microcracks. The lifetime is higher than MTTF of epoxy-molded packages. Producing more test dice will provide more accurate statistical models and help us further understand MEMS reliability.

Vacuum sealing processes will be preferred for motion, infrared, pressure sensors, resonant, and tunneling devices, RF oscillators and display devices, to reduce package size and improve performance. Wafer-to-wafer bonding has been employed to hermetically seal micromachines. This capability enables standard CMOS processes and integrated MEMS devices to be packaged at the chip level. A cap wafer and the CMOS wafer with a freed micromachined structure can be vacuum sealed via wafer-to-wafer bonding. Electroplating can be adopted to apply the solder on the cap layer since it offers perhaps the best combination of solder thickness and uniformity and hermeticity (Sparks, 2001).

The vacuum quality (Q) of a resonant device is often used to gauge the vacuum level of the package. Q values can vary from 100 to 200 in 1 atmosphere to 1,000 to 100,000 in vacuum, depending on the pressure and material. Using wafer-to-wafer bonding and packaging techniques, the reliability of resonant devices can be improved by avoiding a reduction of Q (vacuum leakage) by adopting solder-reflow methods, since it allows vacuum packaging to be accomplished without planar zed CMOS surface topography. A bond pad capped with a noble metal like gold rather than only aluminum can improve the reliability of a product due to

increased resistance to corrosion. A gold-capped bond pad also attracts lesser silicon slurry during wafer sawing.

10.0 Conclusions

The contributors to the roadmap present this chapter as one of the cornerstones to the commercial proliferation of MEMS devices. They describe how robust reliability and the effective measurement of functionality grounded on metrology is often the limiting factor to MEMS commercialization. They further elaborate that the man-years of effort required to obtain a robust knowledge in this arena for Microsystems is daunting. This chapter is heavily linked to other chapters of the roadmap, perhaps most especially to the Commercialization and Standardization chapters. The chapter contributors highlight the link between a robust reliability, metrology and test infrastructure, which is linked to standards in testing, and the effective commercialization of any segment of the microsystems arena.

The contributors highlight the nature of microsystems as a “Disruptive” technology that requires that reliability and commercialization go hand in hand. Robust knowledge and understanding of the materials used in manufacture, device function and the environment in which it is designed to operate is necessary for a reliable system. The fact that many microsystems have already passed through the reliability gauntlet is also discussed in the chapter, as well as the fact that some MEMS devices such as optical cross-connect switches are well along in the process.

The contributors have provided a taxonomy that speaks directly to the difficulties involved in test, reliability and metrology by the nature of the device itself. We further provide discussions on the relationship between new materials introduction and the gap that creates in the learning needed for a reliable process. We further indicate the nature of functional testing in MEMS and the interaction and importance that packaging plays in a robust MEMS device and the performance of the resultant microsystems. We integrate this chapter with the chapter discussing design test and simulation and the role that they play in developing a reliable process and discuss this in detail here and in the chapter on Design, Simulation and Modeling.

MEMS/MST quality assurance is only going to be determined from stable, mature and large-scale production that excludes MEMS/MST laboratory developers and fledgling MEMS/MST

foundries. This fledgling MEMS/MST community does not have the diagnostic measurement and testing tools, or the experienced operators, that the large mature MEMS/MST producers or national laboratories do.

Expert assistance would shorten development cycles, resolve fabrication problems and generally improve competitiveness. Government laboratories are chartered to make technological contributions of national interest that encompasses the shepherding of a fledgling MEMS/MST community. MANCEF, on behalf of its members, may implement such programs with various government laboratories. The utility of such technological assistance would be invaluable to fledgling producers, accelerating them into the stable, mature and large-scale production regime.

Finally, the contributors to this chapter discuss process reliability, which is interconnected with both the Foundries chapter and the chapters on IC and Non-IC Processing. Reliability is a main issue in characterizing many of the IC and non-IC-related processes. The eventual shakeout of these processes will be determined by reproducible highly repeatable processes, which can be characterized. The Foundries chapter is directly linked to this chapter. In the Foundries chapter, our contributors link tolerance and efforts to achieve ISO certification to a robust developing foundry infrastructure.

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